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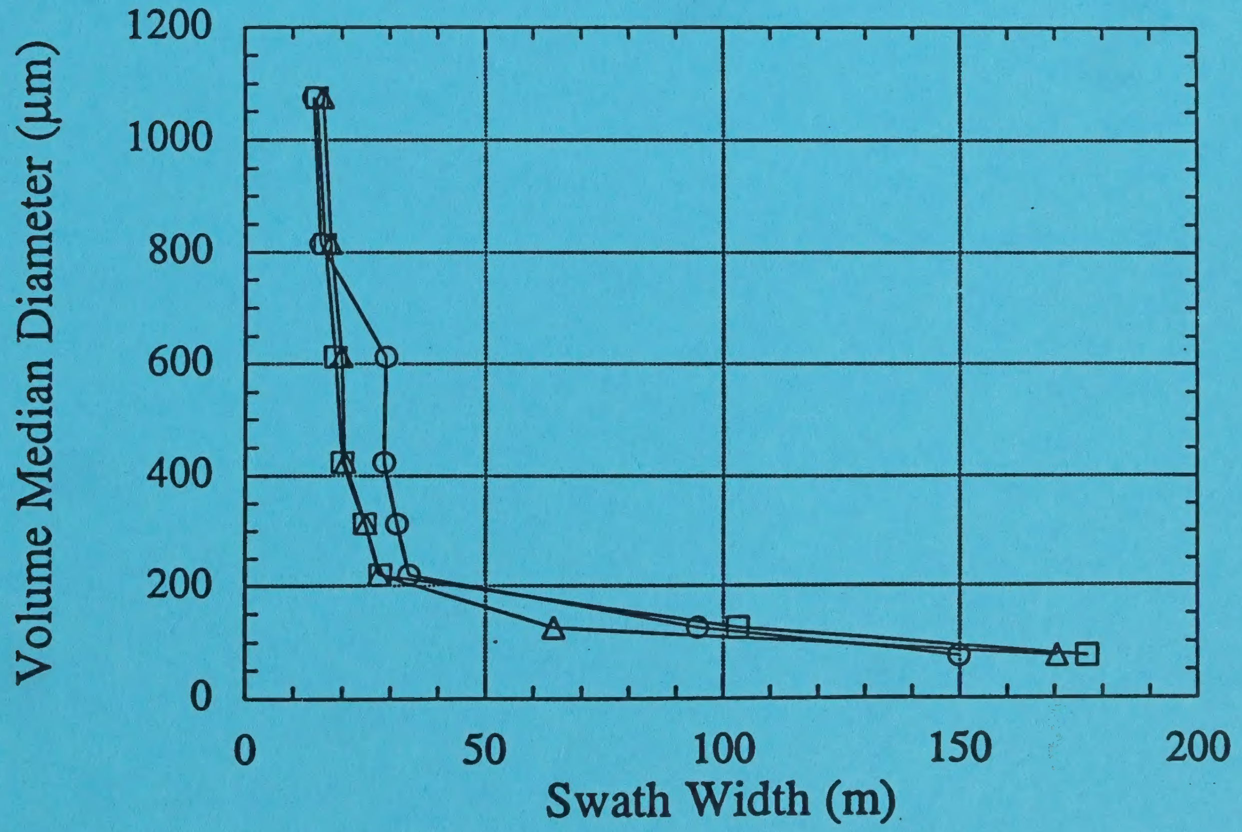
EVALUATION OF THE FSCBG AERIAL SPRAY MODEL'S NEAR-WAKE SENSITIVITY TO SELECTED INPUT PARAMETERS



FHTET 96-30
November 1996

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Apply ps. beneficial insects, fish, and wildlife. Do not apply pesticides where there is danger of drift when honey bees or other pollinating insects are visiting plants, or in ways that may contaminate water or leave illegal residues.

Avoid prolonged inhalation of pesticide sprays or dusts; wear protective clothing and equipment, if specified on the label.

If your hands become contaminated with a pesticide, do not eat or drink until you have washed. In case a pesticide is swallowed or gets in the eyes, follow the first aid treatment given on the label, and get prompt medical attention. If a pesticide is spilled on your skin or clothing, remove clothing immediately and wash skin thoroughly.

NOTE: Some States have restrictions on the use of certain pesticides. Check your State and local regulations. Also, because registrations of pesticides are under constant review by the U.S Environmental Protection Agency, consult your local forest pathologist, county agriculture agent, or State extension specialist to be sure the intended use is still registered.

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Overview

The near-wake portion of the USDA Forest Service aerial application prediction model FSCBG (Forest Service Cramer-Barry-Grim) is applied to an extensive sensitivity study of the most important variables affecting the aerial application of herbicides and pesticides in the United States and New Zealand. Building on previous work, this study specifically examines the prediction by the Lagrangian trajectory model of swath width, and the recovery of buffer distance off-target and downwind from a spray block. Thirteen separate variable effects (aircraft type, boom width, release height, spraying speed, aircraft weight, wind direction, wind speed, nonvolatile fraction, temperature and relative humidity combination, nozzle type, specific gravity, release height and wind speed combination, and release height, temperature and relative humidity combination) are examined, leading to a total of 3100 computer runs. Findings from the study include, as before, the importance of release height and wind speed, but now also include details on the effects of aircraft type and drop size distribution. Results are presented in graphical form, for ease of interpretation, and will constitute the Training Module in SpraySafe Manager and the Near-Wake Sensitivity Library in FSCBG version 5.0, for ready access by the model user.

This work forms a part of the close cooperation between the USDA Forest Service and New Zealand Forest Research Institute during November 1995, to initiate development of a stand-alone, highly user-friendly decision support system (called SpraySafe Manager) that will take advantage of the accurate predictions from FSCBG, but with a simple, easy-to-use and easy-to-understand user interface.

The author wishes to acknowledge the support of the USDA Forest Service (through John Barry) and the New Zealand Forest Research Institute (through John Tustin), and the advice and program focus provided by Brian Richardson.

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1. Introduction

Over the last twenty-five years the USDA Forest Service has been pursuing the development of computer models to predict the dispersion and deposition of aerially released material. The two current models available are AGDISP (Bilanin et al. 1989) and FSCBG (Teske et al. 1993). FSCBG (for Forest Service Cramer-Barry-Grim) predicts the transport and behavior of pesticide sprays released from aircraft, influenced by the aircraft wake and local atmospheric conditions, through downwind drift and deposition to total accountancy and environmental fate. The AGDISP (for AGricultural DISPersal) near-wake model, contained within FSCBG, solves a Lagrangian system of equations for the position and position variance of spray material released from each nozzle on the aircraft. The FSCBG far-wake model begins with the results of AGDISP at the top of a canopy or near the ground, and solves a Gaussian diffusion equation to recover ground deposition. The combination of AGDISP within FSCBG presents a powerful predictive tool for dispersal of spray material from multiple line sources, including evaporation, canopy penetration, and accountancy and environmental fate.

FSCBG has undergone continued development, refinement and enhancement over its lifetime (Dumbauld, Bjorklund and Saterlie 1980; Bjorklund, Bowman and Dodd 1988; Curbishley and Skyler 1989; Teske and Curbishley 1991, 1994). Model validation is an ongoing priority with the model (validation summaries may be found in Teske, Barry and Thistle 1994 and Teske, Thistle and Barry 1996b). A real-time version of FSCBG for GPS/GIS applications has also been developed (Teske, Barry and Thistle 1996a). The near-wake portion of the model has been selected by the Spray Drift Task Force (SDTF), and renamed by them as AgDRIFT, as the model of choice for pesticide registration (Teske et al. 1996). The Canadian Spray Drift Task Force has decided on the near-wake model as well (accessing it through the FSCBG interface) as its model of choice for buffer zone prediction (R. E. Mickle, 1995, private communication). Plans are underway to include FSCBG in three developing decision support systems: GypsES (in its Spray Advisor), the gypsy moth decision support system under development by the USDA Forest Service, Morgantown, WV, to monitor the spread of the gypsy moth and track the spray projects contracted to contain its movement; SpraySafe Manager, an aerial application decision support system under development by the USDA Forest Service, Davis, CA, and New Zealand Forest Research Institute (FRI) for herbicide use; and ASPEX, a mosquito control decision support system under development by the USDA and the U. S. Air Force Reserve.

One of the significant areas in which predictive models can have great impact is in revealing trends in effects due to changes in input parameters. This is especially true in the case of complex problems, such as the aerial application of pesticides and herbicides, where the wake formed by the aircraft creates a flow field superimposed over the ambient meteorological background, and into which spray material is released. The effect of different nozzles ejecting the spray material (and the resulting drop size distributions), ambient wind speed, release height, evaporation, and any other parameter affecting this problem, has the possibility of significantly altering the downwind deposition pattern created by the typical spray scenario.

Previous work (Teske and Barry 1993) provided an initial assessment of the importance of all inputs into the FSCBG model. However, when looking for model trends, particularly when these trends could be instructional within decision support systems, it is important to deal with results that have direct bearing on the aerial application problem of interest. In the case of SpraySafe Manager, the two most important parameters

have been judged to be: (1) the swath width of the aircraft in its various parametric scenarios, and (2) some measure of the buffer distance that would result from spraying in each configuration. Richardson (1995) outlines the desired features in the SpraySafe Manager decision support system, while Teske (1996) reviews the initial connection of FSCBG with it.

One of the important modules envisioned in any decision support system is that of Training. This module would enable the user to examine "what-if" scenarios by changing inputs to the model and quickly recovering trends, without spending time waiting for the model to run through its paces for each of the chosen variations. A sizable database of previously generated FSCBG runs is therefore needed to enable interpolation for the answers to the questions posed by the user. The purpose of this report is to detail the generation of this database, for the near-wake model, and the trends interpreted from the model runs needed to create sufficient data to achieve the Training and Sensitivity Library functions desired.

This paper first reviews the previous sensitivity study and the philosophy behind it, then summarizes the approach taken in this extended near-wake sensitivity study and the role it will play in SpraySafe Manager and its presumed role in other decision support systems as well, and finally the interpretation of FSCBG results within this collective framework.

2. Review of the Previous Parametric Sensitivity

While it is true that a good approach to any model problem should include some examination of the sensitivity of results to model inputs (we do this as a matter of policy in every calculation we undertake), a dedicated parametric study of all of the inputs to FSCBG was not reported until Teske and Barry (1993). This section of the report reviews the approach undertaken in that study, and the results that were revealed by it.

The driving idea in Teske and Barry (1993) was this: model development had reached the stage of providing a workable personal computer version of FSCBG (including an ever-expanding user database for the model and on-going validation against numerous field studies); however, the number of inputs needed to run the model -- even in its simplest level -- was potentially staggering, especially to a first-time user. It was deemed important, therefore, to examine all model inputs to see which of these were more influential in controlling the solution to a sample problem, and which should therefore be accurately determined, to enable a consistent prediction of the specific problem at hand. It was expected that from such a study we would also determine which inputs only needed to be known approximately because they were not all that important.

It quickly became apparent that the study should include an examination of every input into FSCBG. Since the approach could easily become overwhelming in the number of model runs to make, Jack Barry and I narrowed our study (to conserve time and cost) by making a series of assumptions:

1. We examined the sensitivity of model changes to only two aircraft -- the Bell JetRanger III helicopter and the Ayres Turbo Thrush fixed-wing aircraft. These aircraft are typically used by the USDA Forest Service for gypsy moth spraying, and were both found in the FSCBG Aircraft Library.

2. We further examined the sensitivity of model changes to only the Beecomist 360A and Micronair AU5000 rotary atomizers, with further sensitivity explored with 8004 fan nozzles -- again, equipment typically used to treat gypsy moth.

3. We selected drop size distributions (from the FSCBG Mass Size Distribution Library) generated from only water and Foray 48B undiluted *Bacillus thuringiensis* (Bt) tested through the selected rotary atomizers and nozzles.

4. Meteorological characteristics were selected as typical for spraying in the Northeast for gypsy moth.

5. Canopy characteristics were selected as those typically encountered as well.

To quantify the results obtained from the study, we developed two nondimensional parameters, Figure of Merit and Mean Horizontal Position:

1. <u>Figure of Merit</u> (FOM) correlated the deposition profile generated by a variation in one of the inputs (the sensitivity variation) to the default (or base case) deposition profile. The algebraic representation was:

$$\frac{FOM}{1+FOM^2}=\frac{\int c_b\, c_s\, dy}{\int \left(c_b^2+c_s^2\right) dy} \tag{1}$$

where $c_b(y)$ is the base case nonvolatile deposition profile, $c_s(y)$ is the resulting sensitivity variation nonvolatile deposition profile, and y is the horizontal downwind distance (measured relative to the centerline of the aircraft). FOM is seen to track linearly with overall differences in the nonvolatile spray deposition pattern, and best represents in-swath or near in-swath changes (if for example $c_s(y)$ is identical to $c_b(y)$, FOM = 1; if $c_s(y)$ is one-half of $c_b(y)$ everywhere, FOM = 0.5).

2. Mean Horizontal Position (MHP) was determined from:

$$MHP=\frac{\int y\, c_s\, dy}{\int c_s\, dy}\,\frac{\int c_b\, dy}{\int y\, c_b\, dy} \tag{2}$$

where MHP defines the moment of the sensitivity variation nonvolatile deposition profile relative to the moment of the base case nonvolatile deposition profile, and best represents the effects of downwind drift. Changes in FOM and MHP with respect to changes in the sensitivity variable from its base case input value are tracked by developing the two factors:

$$\text{FOM Factor}=\frac{FOM-1}{V_s/V_b-1} \tag{3}$$

$$\text{Drift Factor}=\frac{MHP-1}{V_s/V_b-1} \tag{4}$$

where V_b is the base case value of the variable and V_s is its sensitivity value. Thus, when a ten percent increase in the sensitivity variable (so that $V_s = 1.1\ V_b$) recovers FOM = 1.1 or MHP = 1.1, their respective FOM Factor or Drift Factor is 1. In this case FOM or MHP reflects a one-for-one correlation with variable sensitivity. When FOM Factor (Eq 3) or Drift Factor (Eq 4) recovers values larger than 1 for a change in an input variable, the value of that variable may then be considered important and the variable needs to be known with some accuracy before running FSCBG. If, on the other hand, FOM Factor or Drift Factor recovers values smaller than 1 for a change in an input variable, that variable may be considered relatively unimportant to FSCBG. Within this structure, all spray scenarios examined could be referenced to each other, and simple comparisons could be made between one aircraft and nozzle configuration and another.

While this approach was not necessarily innovative, what was attempted was to rank input variables by their order of sensitivity, and to quantify their importance to aerial application by developing parameters that reflect the deposition pattern generated by each spray scenario. With these parameters (FOM Factor and Drift Factor), we were able to

rank changes in output to changes in input, and to generate a quantitative measure of sensitivity.

These results are presented in Table 1 for completeness. If it is assumed that aircraft and spray material characteristics are essentially given (especially if a specific aircraft, with a specific nozzle arrangement, must be used to spray a specific pesticide tank mix over a specific forest or agricultural field), then the variables:

Aircraft Wing Span
Nozzles Horizontal Position
Spray Material Specific Gravity
Canopy Height
Helicopter Rotor Diameter
Spray Material Volume Median Diameter

will be known accurately. This is good, since Table 1 shows that these variables exhibit sensitivity factors greater than 1. The important variables in Table 1, of course, are the ones difficult to control, namely:

Release Height
Aircraft Spraying Speed
Barometric Pressure
Wind Direction
Wind Speed

and therefore their values must be known as accurately as possible to gain confidence in any model prediction of downwind deposition and drift.

The results from Table 1 are, for the most part, not surprising; in fact, if some of the parameters did not show up in the table where they had, we would have indeed been surprised. Further down Table 1, however, some of the results -- such as the apparent insensitivity to temperature and relative humidity effects, and the low sensitivity to aircraft weight -- call into question the approach we took to parameterize sensitivity effects, and suggest that we include these variables in any detailed, follow-up study, such as the one here undertaken.

Table 1. Previous sensitivity factors generated by FSCBG predictions (from Teske and Barry 1993).

Variable	Maximum of FOM Factor and Drift Factor[1]
Aircraft Wing Span	4.819
Nozzles Horizontal Position	3.904
Release Height	2.843
Spray Material Specific Gravity	2.622
Aircraft Spraying Speed	2.118
Canopy Height	2.062
Barometric Pressure	1.853
Wind Direction	1.716
Wind Speed	1.701
Helicopter Rotor Diameter	1.560
Spray Material Volume Median Diameter	1.154
Aircraft Weight	0.832
Atmospheric Vortex Decay Coefficient	0.650
Propeller Efficiency	0.575
Canopy Tree Envelope Width	0.565
Nozzles Vertical Position	0.506
Propeller Blade RPM	0.464
Helicopter Blade RPM	0.419
Canopy Penetration Probability	0.418
Atmospheric Net Radiation Index	0.404
Temperature	0.398
Propeller Radius	0.386
Canopy Tree Density	0.384
Aircraft Drag Coefficient	0.347
Aircraft Planform Area	0.347
Biplane Wing Separation Distance	0.344
Spray Material Volatile Fraction	0.319
Engine Vertical Position	0.269
Spray Material Evaporation Rate	0.243
Engine Axial Position	0.185
Jet Engine Thrust	0.155
Relative Humidity	0.150
Number of Drop Sizes in Drop Distribution	0.119
Number of Nozzles	0.108
Nozzles Axial Position	0.104
Canopy Leaf Element Size	0.072
Jet Engine Radius	0.048

1. FOM Factor is defined by Eq 3, Drift Factor by Eq 4; here the larger value of the factors is displayed as the sensitivity factor.

3. Study Philosophy and Approach

FSCBG is a powerful computer model for predicting the behavior of aerially released material. Its near-wake model (patterned on AGDISP) provides a computationally efficient way of determining the ground deposition pattern beneath a spray aircraft. Making changes to inputs in a consistent manner, and then running the model (generally in a batch configuration overnight on available 486 or Pentium personal computers) provides a straightforward way to generate the needed deposition patterns. Post-processing by other analysis programs then generates the results desired.

Based on the previous sensitivity work, and given the needs and desires of the principals in this matter (Jack Barry for the USDA Forest Service and Brian Richardson for New Zealand Forest Research Institute) and what could actually be achieved from a realistic time and cost standpoint, a series of communications revealed several areas of common interest, and common need:

1. Aircraft Type and Base Case Configurations (24 model runs)

Whereas the previous sensitivity study concentrated on only two aircraft (Bell JetRanger III and Ayres Turbo Thrush), here we wish to expand our study to include the most commonly used aircraft in both countries (the United States and New Zealand), and the most commonly used atomizer setups. Six aircraft (three fixed-wing and three helicopter) were each selected by Jack Barry and Brian Richardson, as summarized in Table 2 (the Bell JetRanger III was common to both of their lists). Aircraft characteristics were taken from the FSCBG aircraft library (which is a compilation of the work of Hardy 1987), with the exception of the Squirrel, whose characteristics were provided by Brian Richardson (1995, private communication). These aircraft were fitted with the two nozzle configurations as summarized in Table 3: for the US helicopters, four Beecomist 360A rotary atomizers and D8/46 nozzles oriented straight back (0 deg) out to 75 percent of the rotor radius (nozzles were placed 0.25 m apart); for the US fixed-wing aircraft, eight Micronair AU5000 rotary atomizers and D8/46 nozzles oriented straight back (0 deg) out to 75 percent of the wing semispan (nozzles again placed 0.25 m apart); and for the NZ helicopters and fixed-wing aircraft, D8/46 nozzles oriented down (at 90 deg) out to 80 percent of the wing semispan or rotor radius (nozzles 0.25 m apart).

The base case drop size distributions were selected from the FSCBG Mass Size Distribution Library (from Skyler and Barry 1991) and from distributions provided by Brian Richardson (1995, private communication). Distributions were selected so as to encapsulate the volume median diameter (VMD) range thought to exist when spraying. The US spray material was water flowing through these nozzles; however, a nonvolatile fraction of 0.4 was used to be consistent with the most common material sprayed for control of the gypsy moth, namely Bt. The NZ spray material was Roundup® with Pulse® added (in two different proportions, generating two distinct drop size distributions), with an expected nonvolatile fraction of 0.085. The drop size distributions obtained from the FSCBG library were fitted to a root/normal function (Teske and Barry 1992) to recover drop diameters below 34 µm. The five base case distributions are shown in Table 4.

Other conditions taken as a part of the base case assumptions are a release height of 5 m for the NZ aircraft and 15 m for the US aircraft (no canopy was considered in this near-wake sensitivity study), an ambient temperature of 20 deg C, relative humidity of 60

percent, wind speed of 5 kph (1.39 m/sec), and a wind direction of 90 deg to the flight line.

All sensitivity variations were run by changing one or more of the input parameters from their base case values, while retaining the base case values for all of the other inputs into the FSCBG model.

2. Boom Width (120 additional model runs)

Boom width sensitivity was examined by varying the maximum horizontal position of the nozzles along the boom, to 50, 60, 70, 90 and 100 percent of the wing span or rotor diameter. The base case widths were 75 percent for US configurations and 80 percent for NZ configurations. The D8/46 nozzles were assumed to be 0.25 m apart along the boom; thus, the number of nozzles varied with the percentage of wing span or rotor diameter for each aircraft in the study. On the other hand the number of rotary atomizers was not changed with change in boom width; rather, their locations were altered to fit within the percentage of wing span or rotor diameter examined.

3. Release (Boom) Height (120 additional model runs)

Release height sensitivity was examined by setting the boom height at 5, 10, 15, 20, 25 and 30 m above the ground. The base case boom heights were 5 m for NZ configurations and 15 m for US configurations.

4. Spraying Speed (114 additional model runs)

Spraying speed sensitivity was examined by changing the speed of the aircraft from 10.3, 20.6, 30.9, 41.2, 51.4 and 61.7 m/sec (20, 40, 60, 80, 100 and 120 knots), eliminating 10.3 m/sec (20 knots) for fixed-wing aircraft and 61.7 m/sec (120 knots) for helicopters (both speeds were out-of-range for these aircraft types). The base case speeds were 20.6 m/sec for helicopters and 41.2 m/sec for fixed-wing aircraft. As the spraying speed increases, in actuality the atomization process should alter the drop size distribution exiting the nozzles. Unfortunately, to include this effect would require data resources (appropriate drop size distributions) that have not been wind-tunnel tested, or cannot yet be determined analytically, even though such an approach is currently being developed (Teske et al. 1996). Thus, the drop size distribution data summarized in Table 4 was used for all spraying speeds. This restriction diminishes the sensitivity of the model to spraying speed, without masking its effect by changing drop size.

To test the specific effect of spraying speed on atomization, we additionally examined the FSCBG drop size distribution database (Skyler and Barry 1991) and extracted three sets of data (for D8 Jet, D8/46 and RD-7 nozzles oriented straight back) at the three spraying speeds 22.4, 44.7 and 67.1 m/sec (50, 100 and 150 mph). These data -- appropriately expanded by the root/normal function -- are summarized in Table 5 (the atomization from the D8/46 nozzle at 44.7 m/sec is the base case condition for that nozzle but at a slightly different speed, and is given in Table 4 with a VMD of 423.9 μm). Only the Ayres Turbo Thrush and Bell JetRanger III (US configuration) were investigated here for the effect of spraying speed on drop size distribution.

5. Aircraft Weight (96 additional model runs)

Aircraft weight sensitivity was examined by arbitrarily changing the weights of the aircraft to 0.5, 0.75, 1, 1.25 and 1.5 times their base case values (displayed previously in

Table 2). The base case values are, of course, for a factor of 1. From previous experience, however, it is anticipated that changing only the aircraft weight will produce a minimal sensitivity (for example, the aircraft weight sensitivity factor in Table 1 is less than 1), because a change in aircraft weight is usually accompanied by a change in other variables as well, as suggested by the following discussion.

The simple equivalence of lift force to aircraft weight W generates the model equation for the vortex circulation strength:

$$\Gamma = \frac{W}{2\,s\,\rho\,U} \tag{5}$$

where Γ is the vortex circulation strength, W is the weight of the aircraft, ρ is atmospheric density, and U is spraying speed. Equation 5 clearly shows that a change in aircraft weight directly changes the vortex strength (this effect of course is included in FSCBG), but we know from experience that the spraying speed U may also change (a lighter aircraft does not necessarily fly at the same speed as a heavier aircraft without adjusting trim, a condition not modeled here). In the field the pilot adjusts flaps to maintain release height at the desired spraying speed, even as the aircraft changes weight because of release of spray material. The change in speed will change the atomization of the spray material through the nozzles, as explained in the spraying speed sensitivity. This effect is not easily quantified here; perhaps the best we can do is merely change the aircraft weight alone, and consider the effect of spraying speed on drop size distribution (as mentioned above) in greater detail.

6. Wind Direction (72 additional model runs)

Wind direction sensitivity was examined by setting the wind direction (relative to the aircraft flight direction) to 0, 30, 60 and 90 deg. A wind direction of 0 deg aligns the wind with the flight direction, and becomes the inwind condition. A wind direction of 90 deg becomes the crosswind condition, and is also the base case wind direction.

7. Wind Speed (72 additional model runs)

Wind speed sensitivity was examined by setting the wind speed (the speed of the wind 2 m above the ground) to 1.39, 2.78, 4.17 and 5.56 m/sec (5, 10, 15 and 20 knots). The speed of 1.39 m/sec (5 knots) is the base case wind speed.

8. Nonvolatile Fraction (120 additional model runs)

Sensitivity of nonvolatile fraction (the ratio of the volume of spray material that does not evaporate to the volume of released spray material) was examined by varying the fraction from 0.085, 0.2, 0.4, 0.6, 0.8 and 1 (no evaporation effects). The base case nonvolatile fractions are 0.085 for NZ configurations and 0.4 for US configurations. Deposition in the sensitivity study is determined for the nonvolatile spray material only.

9. Wet Bulb Temperature Depression (144 additional model runs)

Sensitivity to ambient temperature and relative humidity was examined with the single parameter of wet bulb temperature depression ΔT_{wb}. Wet bulb temperature depression combines the ambient (dry bulb) temperature and relative humidity into one convenient variable, through solution of the Carrier equation (Jennings and Lewis 1950, from Carrier and Mackey 1937). In the sensitivity study ΔT_{wb} was varied from 0, 2, 4, 6,

8, 10 and 12 deg C, thereby including ambient temperature variations from 5 to 25 deg C and relative humidity variations from 20 to 95 percent, and providing a simple combined effect for these two model inputs (a plot of wet bulb temperature depression as a function of ambient temperature and relative humidity is shown in Figure 1). A value of $\Delta T_{wb} = 0$ deg C corresponds to no evaporation effects, and was determined in the nonvolatile fraction sensitivity. The base case values of 20 deg C temperature and 60 percent relative humidity recover a value of $\Delta T_{wb} = 4.87$ deg C.

10. Nozzle Type (78 additional model runs)

Nozzle type sensitivity required us to consider several other nozzles typically used in the US and NZ (beyond the base case ones), and is in truth a sensitivity on drop size distribution. To include the effect of VMD across the whole spectrum of values, we decided on a total of eight drop size distributions: Micronair AU5000 (with a VMD of 74.5 μm); Beecomist 360A (with a VMD of 125.1 μm); D8/45 (220.8 μm); D8/46 (314.0 μm, 423.9 μm and 613.0 μm); Delafoam (815.5 μm); and D6 Jet (1075.5 μm). Nozzles were placed 0.25 m apart (even for the Micronair and Beecomist atomizations because here we are more interested in atomization effects). Drop size distributions were obtained from the FSCBG database (Skyler and Barry 1991) and Brian Richardson (1995, private communication), and show variation because of the nozzle selected and the tank mix additives. The Beecomist drop size distribution and the D8/46 drop size distribution with VMD = 423.9 μm are two of the base cases for US configuration helicopters; the Micronair drop size distribution and the D8/46 drop size distribution with VMD = 423.9 μm are two of the base cases for US configuration fixed-wing aircraft; and the D8/46 drop size distributions with VMD = 314.0 μm and 613.0 μm are the base case atomizations for NZ configuration aircraft. The new atomizations (beyond the base case ones) are given in Table 6.

11. Specific Gravity (150 additional model runs)

Specific gravity sensitivity was examined by varying specific gravity from 0.8, 0.9, 1, 1.1 and 1.2 for the eight drop size distributions discussed above (spanning the VMD range). A specific gravity of 1 was either the base case or run for the nozzle type sensitivity. For these calculations we further chose to examine only four aircraft: Ayres Turbo Thrush (US configuration); Bell JetRanger III (both configurations); and Fletcher (NZ configuration) to reduce the number of calculations necessary.

A further study of specific gravity involved comparing drop size distribution effects against water for tank mixes with nonunity specific gravity. We believe that a change in specific gravity should be accompanied by a variation in the atomization, an effect that cannot be duplicated in the simple specific gravity sensitivity described in the previous paragraph. To effect this additional study, we extracted all pertinent cases from the FSCBG library (Skyler and Barry 1991) that contain side-by-side wind tunnel data for water and spray material through various nozzle types. An examination of the data recovered the combinations:

Nozzle Type	Spray Material	Specific Gravity	Nonvolatile Fraction
8004	Foray 48B (Bt)	1.16	0.400
8006	Gypcheck (virus)	1.10	0.205

8010	TM-Biocontrol (virus)	1.10	0.303
8010	Gypcheck (virus)	1.10	0.205
Micronair	TM-Biocontrol (virus)	1.10	0.303
Micronair	Gypcheck (virus)	1.10	0.205
Beecomist	TM-Biocontrol (virus)	1.10	0.303

These atomizations were then compared with water through the same nozzles at the same flight conditions. For consistency we assumed that the water behaved with the same nonvolatile fractions as the nonwater spray materials. Since this investigation was of US concern, only the Ayres Turbo Thrush and Bell JetRanger III (US configuration) were used in this additional specific gravity sensitivity. The additional 14 drop size distributions are summarized in Table 7.

12. Release Height and Wind Speed (688 additional model runs)

To overcome any bias in the base case conditions, we decided to develop a combined sensitivity effect involving a systematic change in release height and wind speed. To make this study computationally effective, we restricted ourselves to four aircraft: Ayres Turbo Thrush (US configuration); Bell JetRanger III (both configurations); and Fletcher (NZ configuration). The study included the eight drop size distributions discussed in the nozzle type sensitivity, and involved changes in release height (5, 10, 15, 20, 25 and 30 m), wind speed (1.39, 2.78, 4.17 and 5.56 m/sec), and nozzle type (to obtain VMD values of 74.5, 125.1, 220.8, 314.0, 423.9, 613.0, 815.5 and 1075.5 µm).

13. Release Height, Temperature and Relative Humidity (1302 additional model runs)

To investigate this combined effect, we interpreted the temperature and relative humidity effects through the single parameter of wet bulb temperature depression ΔT_{wb}. Again, we restricted ourselves to four aircraft: Ayres Turbo Thrush (US configuration); Bell JetRanger III (both configurations); and Fletcher (NZ configuration). The study included the eight drop size distributions discussed in the nozzle type sensitivity, and involved changes in release height (5, 10, 15, 20, 25 and 30 m), wet bulb temperature depression (0, 2, 4, 6, 8, 10 and 12 deg C), and nozzle type (to obtain VMD values of 74.5, 125.1, 220.8, 314.0, 423.9, 613.0, 815.5 and 1075.5 µm).

In total, then, this sensitivity study explored more details about FSCBG model sensitivity (beyond Teske and Barry 1993) with 3100 computer runs. Predictions were made by the author on five personal computers in New Zealand, while the author was there working on the development of SpraySafe Manager. Additional calculations were made by the author on three personal computers at Continuum Dynamics, Inc., after the author returned to the United States.

Once predictions were obtained for the deposition patterns from FSCBG, the approach taken to interpret the results involved the generation of two parameters of most interest to the Training Module being developed for SpraySafe Manager, and to other decision support systems as well:

1. Swath Width. Overlapping adjacent deposition patterns until a composite in-swath deposition is achieved, with a coefficient of variation (COV) of 30 percent (Teske, Twardus and Ekblad 1990).

2. Buffer Distance. Overlapping 20 flight lines (as suggested in Teske et al. 1996), then finding the distance downwind where ten percent of the nonvolatile application rate is achieved. This level is somewhat arbitrary, and is used here merely as a basis for comparison between sensitivity changes. Since the deposition files have been saved, once a specific level of deposition is known (for perhaps a specific dose response or some regulatory number), these files may be quizzed to recover the appropriate buffer distances in that application.

The results, discussed in the next section of this report, demonstrate the sensitivity of Swath Width and Buffer Distance (where examined) to changes in FSCBG model inputs as detailed in the 13 areas considered above.

Table 2. Aircraft examined in the extended near-wake sensitivity study.

Name	Type	Country	Wing Span or Rotor Diameter (m)	Weight (N)
Air Tractor AT-301	fixed-wing	US	13.78	25900
Ayres Turbo Thrush	fixed-wing	US	13.54	26900
Bell 205A	helicopter	US	14.64	34200
Bell JetRanger III	helicopter	US/NZ	10.18	9700
Cessna Ag Wagon	fixed-wing	NZ	12.68	12300
Fletcher	fixed-wing	NZ	12.80	16800
Hiller Soloy Turbo	helicopter	US	10.80	10500
Hughes 300C	helicopter	NZ	8.16	6900
Hughes Cayuse 500C	helicopter	NZ	8.04	8100
Schweizer Ag Cat	fixed-wing	US	12.92	23000
Squirrel	helicopter	NZ	10.66	14100

Table 3. Base case conditions for the extended near-wake sensitivity study.

Fixed-Wing Aircraft	Nozzle Type	VMD (μm)
US Configuration	Micronair AU5000 (8) D8/46 straight back	74.5 423.9
NZ Configuration	D8/46 down (0.25 percent)* D8/46 down (1 percent)	613.0 314.0
Spraying Speed	41.2 m/sec (80 knots)	

Helicopters	Nozzle Type	VMD (μm)
US Configuration	Beecomist 360A (4) D8/46 straight back	125.1 423.9
NZ Configuration	D8/46 down (0.25 percent) D8/46 down (1 percent)	613.0 314.0
Spraying Speed	20.6 m/sec (40 knots)	

Country	Flow Rate (L/ha)	Tank Mix	Boom Width (percent)	Release Height (m)	Nonvolatile Fraction
US	100	insecticide	75	15	0.4
NZ	100	herbicide	80	5	0.085

Temperature	20 deg C
Relative Humidity	60 percent
Wind Speed	1.39 m/sec (5 kph)
Wind Direction	90 deg to the flight path

* Percentage refers to percent by volume of Pulse® added to Roundup®.

Table 4. Base case drop size distributions for the extended near-wake sensitivity study.

Average Diameter (µm)	Micronair AU5000	Beecomist 360A	D8/46 (1%) 90 deg	D8/46 0 deg	D8/46 (0.25%) 90 deg
13.92	0.04025	0.00019	0.00215	0.00261	0.00165
20.84	0.02576	0.00044	0.00130	0.00124	0.00100
24.20	0.03616	0.00042	0.00145	0.00068	0.00155
28.15	0.04614	0.00077	0.00125	0.00087	0.00150
32.55	0.05406	0.00138	0.00170	0.00107	0.00195
37.72	0.05529	0.00263	0.00305	0.00139	0.00250
43.73	0.04629	0.00504	0.00435	0.00181	0.00290
50.64	0.04536	0.00952	0.00535	0.00234	0.00360
58.76	0.05649	0.01801	0.00610	0.00313	0.00505
68.12	0.07976	0.03210	0.00755	0.00414	0.00720
78.99	0.10494	0.05409	0.01125	0.00555	0.00905
91.62	0.11640	0.08445	0.01740	0.00747	0.01025
106.30	0.10296	0.12096	0.02490	0.01009	0.01085
123.21	0.09850	0.15320	0.03080	0.01351	0.01370
142.75	0.04950	0.16614	0.03384	0.01804	0.01840
165.28	0.02730	0.14984	0.03820	0.02388	0.02180
191.33	0.01460	0.10884	0.05037	0.03136	0.02526
221.90	0.00825	0.06104	0.07212	0.04128	0.02856
256.93	0.00495	0.02340	0.13992	0.05214	0.03270
298.05	0.00310	0.00625	0.11190	0.06608	0.04425
345.58	0.00150	0.00116	0.11238	0.08015	0.04746
400.73	0.00080	0.00017	0.10740	0.09335	0.04911
464.80	0.00050	0.00002	0.08485	0.10218	0.05481
538.44	0.00030		0.05607	0.10512	0.07044
623.57	0.00020		0.04365	0.09900	0.08610
722.77	0.00015		0.03290	0.08535	0.09215
837.94	0.00005		0.01965	0.06528	0.08545
971.71	0.00005		0.01135	0.04287	0.07196
1126.43	0.00005		0.00755	0.02312	0.05967
1305.79	0.00005		0.00480	0.01004	0.05136
1513.60			0.00285	0.00349	0.04491
1754.03			0.00195	0.00099	0.04206
VMD (µm)	74.5	125.1	314.0	423.9	613.0

Table 5. Drop size distributions for part of the spraying speed sensitivity study (all nozzles are oriented at 0 deg).

Average Diameter (μm)	RD-7 67.1 m/sec	D8/46 67.1 m/sec	D8 Jet 67.1 m/sec	RD-7 44.7 m/sec
13.92	0.00022	0.00050	0.00055	0.00081
20.84	0.00024	0.00049	0.00035	0.00044
24.20	0.00017	0.00033	0.00021	0.00025
28.15	0.00027	0.00049	0.00028	0.00033
32.55	0.00039	0.00068	0.00037	0.00042
37.72	0.00062	0.00103	0.00051	0.00056
43.73	0.00098	0.00156	0.00071	0.00076
50.64	0.00158	0.00238	0.00099	0.00102
58.76	0.00265	0.00374	0.00143	0.00143
68.12	0.00440	0.00582	0.00206	0.00198
78.99	0.00739	0.00913	0.00302	0.00280
91.62	0.01236	0.01425	0.00447	0.00400
106.30	0.02034	0.02194	0.00666	0.00575
123.21	0.03218	0.03272	0.00986	0.00823
142.75	0.04890	0.04728	0.01453	0.01179
165.28	0.07056	0.06560	0.02112	0.01674
191.33	0.09640	0.08725	0.03028	0.02358
221.90	0.12453	0.11142	0.04305	0.03322
256.93	0.14048	0.12670	0.05802	0.04473
298.05	0.14448	0.13468	0.07740	0.06016
345.58	0.12348	0.12271	0.09730	0.07716
400.73	0.08850	0.09665	0.11466	0.09535
464.80	0.05007	0.06336	0.12425	0.11034
538.44	0.02076	0.03226	0.12089	0.11748
623.57	0.00629	0.01246	0.10404	0.11472
722.77	0.00144	0.00363	0.07832	0.10026
837.94	0.00026	0.00082	0.04869	0.07660
971.71	0.00004	0.00016	0.02380	0.04935
1126.43	0.00001	0.00003	0.00884	0.02536
1305.79			0.00254	0.01017
1513.60			0.00059	0.00317
1754.03			0.00012	0.00080
VMD (μm)	240.5	247.5	406.8	463.7

Table 5. Drop size distributions for part of the spraying speed sensitivity study (all nozzles are oriented at 0 deg) (concluded).

Average Diameter (μm)	D8/46 22.4 m/sec	D8 Jet 44.7 m/sec	RD-7 22.4 m/sec	D8 Jet 22.4 m/sec
13.92	0.00040	0.00010	0.00011	0.00008
20.84	0.00023	0.00004	0.00004	0.00003
24.20	0.00014	0.00002	0.00002	0.00001
28.15	0.00018	0.00003	0.00003	0.00002
32.55	0.00023	0.00004	0.00004	0.00002
37.72	0.00032	0.00005	0.00005	0.00003
43.73	0.00043	0.00006	0.00006	0.00004
50.64	0.00060	0.00008	0.00008	0.00005
58.76	0.00086	0.00011	0.00011	0.00006
68.12	0.00123	0.00015	0.00014	0.00008
78.99	0.00179	0.00021	0.00019	0.00011
91.62	0.00264	0.00030	0.00027	0.00015
106.30	0.00394	0.00044	0.00039	0.00021
123.21	0.00588	0.00064	0.00056	0.00030
142.75	0.00879	0.00096	0.00081	0.00043
165.28	0.01307	0.00145	0.00121	0.00063
191.33	0.01928	0.00223	0.00183	0.00094
221.90	0.02842	0.00353	0.00284	0.00146
256.93	0.04000	0.00550	0.00436	0.00223
298.05	0.05595	0.00881	0.00690	0.00354
345.58	0.07440	0.01381	0.01074	0.00559
400.73	0.09515	0.02144	0.01663	0.00886
464.80	0.11424	0.03252	0.02536	0.01399
538.44	0.12397	0.04716	0.03720	0.02150
623.57	0.12376	0.06604	0.05304	0.03238
722.77	0.10896	0.08905	0.07320	0.04764
837.94	0.08295	0.11280	0.09610	0.06708
971.71	0.05253	0.12999	0.11814	0.09010
1126.43	0.02606	0.13566	0.13090	0.11358
1305.79	0.00987	0.12299	0.13174	0.13027
1513.60	0.00286	0.09575	0.11442	0.13573
1754.03	0.00066	0.06156	0.08505	0.12229
VMD (μm)	483.2	932.2	1029.0	1247.3

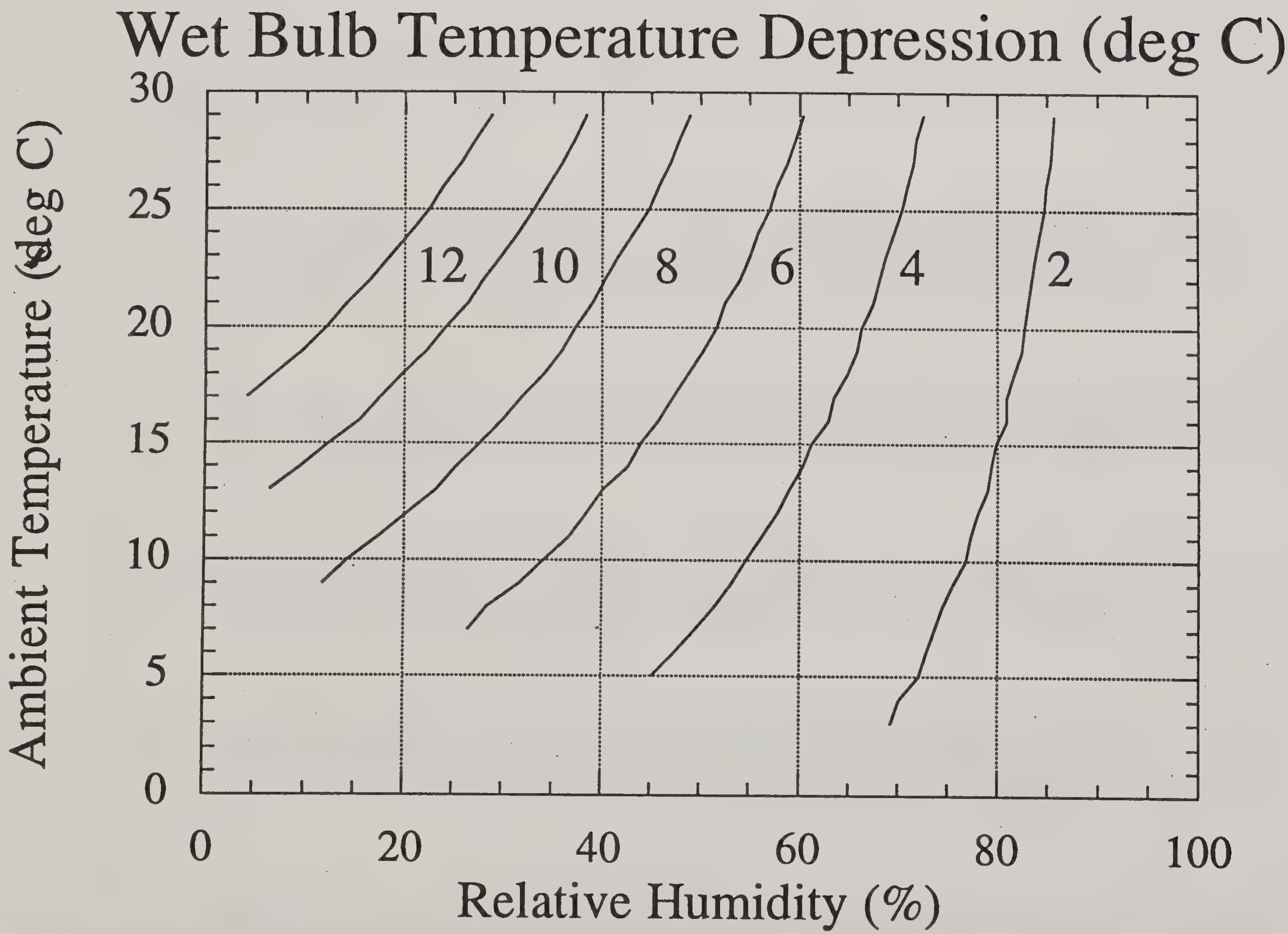

Figure 1. The relationship between ambient temperature, relative humidity and wet bulb temperature depression. Over a range of temperature between 0 and 30 deg C, and relative humidity between 0 and 100 percent, the wet bulb depression varies between 0 and 12 or higher, as shown by the curves on the figure.

Table 6. Additional drop size distributions for the nozzle type sensitivity.

Average Diameter (μm)	D8/45 0 deg	Delafoam 0 deg	D6 Jet 0 deg
13.92	0.00015	0.00025	0.00255
20.84	0.00019	0.00010	0.00050
24.20	0.00014	0.00005	0.00030
28.15	0.00023		0.00005
32.55	0.00035		
37.72	0.00057		
43.73	0.00095	0.00010	
50.64	0.00159	0.00030	
58.76	0.00278	0.00040	0.00010
68.12	0.00481	0.00060	0.00005
78.99	0.00841	0.00065	
91.62	0.01456	0.00085	
106.30	0.02460	0.00180	0.00065
123.21	0.03960	0.00410	0.00110
142.75	0.06048	0.00680	0.00105
165.28	0.08675	0.00615	0.00080
191.33	0.11622	0.00490	0.00005
221.90	0.14280	0.00735	
256.93	0.15096	0.01600	0.00445
298.05	0.13909	0.03300	0.01635
345.58	0.10428	0.03774	0.01595
400.73	0.06228	0.03280	0.00395
464.80	0.02738	0.03260	0.00675
538.44	0.00845	0.05196	0.03268
623.57	0.00193	0.09685	0.06648
722.77	0.00035	0.12194	0.09230
837.94	0.00005	0.12194	0.10866
971.71	0.00001	0.10632	0.11856
1126.43		0.09105	0.12495
1305.79		0.08100	0.13174
1513.60		0.07288	0.13384
1754.03		0.06944	0.13615
VMD (μm)	220.8	815.5	1075.5

Table 7. Drop size distributions for part of the specific gravity sensitivity.

Average Diameter (μm)	Micronair AU5000 water	Micronair AU5000 TM-Biocontrol	Micronair AU5000 water	Micronair AU5000 Gypcheck	Beecomist 360A water
13.92	0.00015	0.00021	0.00012	0.00011	0.00010
20.84	0.00043	0.00049	0.00022	0.00019	0.00016
24.20	0.00045	0.00047	0.00019	0.00016	0.00013
28.15	0.00089	0.00087	0.00032	0.00027	0.00021
32.55	0.00169	0.00155	0.00054	0.00044	0.00035
37.72	0.00343	0.00294	0.00099	0.00078	0.00060
43.73	0.00695	0.00561	0.00183	0.00141	0.00108
50.64	0.01370	0.01050	0.00338	0.00256	0.00195
58.76	0.02662	0.01965	0.00646	0.00481	0.00365
68.12	0.04752	0.03454	0.01200	0.00887	0.00676
78.99	0.07848	0.05739	0.02184	0.01620	0.01247
91.62	0.11772	0.08830	0.03802	0.02860	0.02244
106.30	0.15696	0.12467	0.06204	0.04791	0.03858
123.21	0.17496	0.15480	0.09295	0.07424	0.06176
142.75	0.16074	0.16515	0.12775	0.10662	0.09185
165.28	0.11592	0.14552	0.15472	0.13909	0.12537
191.33	0.06292	0.10338	0.16227	0.15832	0.15224
221.90	0.02362	0.05640	0.14176	0.15672	0.16236
256.93	0.00571	0.02096	0.09715	0.12327	0.13979
298.05	0.00100	0.00545	0.05133	0.07876	0.09950
345.58	0.00014	0.00100	0.01849	0.03612	0.05274
400.73	0.00002	0.00015	0.00459	0.01148	0.01971
464.80		0.00002	0.00083	0.00255	0.00507
538.44			0.00012	0.00043	0.00094
623.57			0.00002	0.00006	0.00015
722.77				0.00001	0.00002
837.94					
971.71					
1126.43					
1305.79					
1513.60					
1754.03					
VMD (μm)	110.5	123.0	161.8	176.2	187.9

Table 7. Drop size distributions for part of the specific gravity sensitivity (continued).

Average Diameter (µm)	Beecomist 360A TM-Biocontrol	8010 water	8010 Gypcheck	8010 water	8010 TM-Biocontrol
13.92	0.00015	0.00019	0.00007	0.00011	0.00011
20.84	0.00022	0.00025	0.00010	0.00014	0.00014
24.20	0.00018	0.00019	0.00008	0.00011	0.00011
28.15	0.00029	0.00030	0.00012	0.00017	0.00017
32.55	0.00047	0.00045	0.00019	0.00027	0.00027
37.72	0.00080	0.00074	0.00032	0.00045	0.00045
43.73	0.00139	0.00122	0.00055	0.00076	0.00076
50.64	0.00242	0.00204	0.00097	0.00130	0.00131
58.76	0.00439	0.00354	0.00177	0.00233	0.00235
68.12	0.00783	0.00606	0.00322	0.00415	0.00420
78.99	0.01390	0.01043	0.00596	0.00746	0.00757
91.62	0.02408	0.01769	0.01097	0.01332	0.01351
106.30	0.03996	0.02920	0.01979	0.02320	0.02354
123.21	0.06208	0.04575	0.03394	0.03838	0.03892
142.75	0.09030	0.06796	0.05496	0.06004	0.06080
165.28	0.12138	0.09485	0.08280	0.08765	0.08865
191.33	0.14632	0.12327	0.11556	0.11904	0.12005
221.90	0.15680	0.14520	0.14776	0.14728	0.14800
256.93	0.13755	0.14784	0.15960	0.15560	0.15568
298.05	0.10128	0.12957	0.14912	0.14160	0.14080
345.58	0.05691	0.09245	0.11106	0.10374	0.10236
400.73	0.02114	0.05187	0.06460	0.05952	0.05814
464.80	0.00656	0.02124	0.02694	0.02464	0.02376
538.44	0.00135	0.00614	0.00768	0.00706	0.00672
623.57	0.00022	0.00134	0.00159	0.00149	0.00140
722.77	0.00003	0.00024	0.00026	0.00025	0.00024
837.94		0.00004	0.00004	0.00004	0.00003
971.71		0.00001	0.00001	0.00001	
1126.43					
1305.79					
1513.60					
1754.03					
VMD (µm)	188.4	211.3	226.3	220.6	219.6

Table 7. Drop size distributions for part of the specific gravity sensitivity (concluded).

Average Diameter (µm)	8006 water	8006 Gypcheck	8004 water	8004 Foray 48B
13.92	0.00171	0.00107	0.00011	0.00130
20.84	0.00114	0.00076	0.00014	0.00078
24.20	0.00068	0.00046	0.00010	0.00045
28.15	0.00091	0.00063	0.00016	0.00060
32.55	0.00118	0.00083	0.00024	0.00077
37.72	0.00162	0.00116	0.00039	0.00104
43.73	0.00223	0.00163	0.00064	0.00142
50.64	0.00306	0.00228	0.00106	0.00193
58.76	0.00433	0.00331	0.00185	0.00271
68.12	0.00606	0.00476	0.00323	0.00377
78.99	0.00857	0.00691	0.00570	0.00532
91.62	0.01211	0.01007	0.01005	0.00755
106.30	0.01706	0.01463	0.01747	0.01074
123.21	0.02360	0.02088	0.02914	0.01508
142.75	0.03220	0.02936	0.04647	0.02104
165.28	0.04308	0.04038	0.06976	0.02890
191.33	0.05643	0.05427	0.09830	0.03912
221.90	0.07300	0.07184	0.13006	0.05262
256.93	0.08900	0.08945	0.14856	0.06728
298.05	0.10494	0.10782	0.15232	0.08525
345.58	0.11328	0.11790	0.12754	0.10128
400.73	0.11382	0.11976	0.08770	0.11196
464.80	0.10212	0.10770	0.04614	0.11610
538.44	0.08065	0.08455	0.01723	0.10650
623.57	0.05529	0.05700	0.00461	0.08785
722.77	0.03138	0.03140	0.00093	0.06352
837.94	0.01398	0.01337	0.00015	0.03796
971.71	0.00486	0.00439	0.00002	0.01802
1126.43	0.00135	0.00114		0.00664
1305.79	0.00031	0.00025		0.00194
1513.60	0.00006	0.00005		0.00047
1754.03	0.00001	0.00001		0.00010
VMD (µm)	305.0	312.8	241.7	370.2

4. Results

FSCBG model predictions were saved as ground deposition patterns of percent applied nonvolatile spray material released. Several numbers could then be generated by examining these predictions in a consistent manner:

1. Maximum deposition. Easily obtained from each deposition pattern.

2. Swath width. Obtained using the approach discussed in Teske, Twardus and Ekblad (1990), by overlapping the predicted single flight line deposition pattern to generate multiple flight line information, then optimizing the results for a coefficient of variation (COV) of 0.3 as suggested by the available literature. The optimized distance between flight lines becomes the swath width (bout width and lane separation are its alternate meanings as well). An alternate definition of swath width is associated with some minimum level of deposition; here, we prefer the COV approach.

3. In-swath deposition. A second result from the optimization is the determination of the mean in-swath deposition level and the standard deviation of the in-swath deposition about the mean. These two numbers feed directly into dose response (Teske 1996).

4. Buffer distance. With the optimized overlapped deposition pattern (with 20 source lines), the distance downwind from the aircraft centerline to a specific level of percent applied nonvolatile can then be determined. Here, for convenience and example, we determine the distance to 10 percent applied nonvolatile from the most downwind aircraft flight line centerline.

This study has created the database necessary to construct a retrieval mechanism with which to provide optimization of inputs to SpraySafe Manager (through its Training Module) and FSCBG (through a Near-Wake Sensitivity Library option). It should be clear that a large amount of data has been generated. Its distillation into SpraySafe Manager will occur with the release of version 1 (expected Spring 1997). Its inclusion into FSCBG will occur with the release of version 5. In the present report we access pieces of the database to see whether some of the findings of the previous sensitivity study (Teske and Barry 1993) continue to hold, and to explore the extent of the usefulness of the accumulated data.

Overlapped in-swath deposition and its standard deviation are best left to SpraySafe Manager development (Teske 1996). It is our anticipation that the overlapped depositions for all cases considered here will reasonably result in deposition levels approaching 100 percent applied nonvolatile, with standard deviations measuring the variability in treatment and nozzle type. Swath width, and buffer distance where necessary, form the basis of our analysis of the predictions made in this sensitivity study.

1. Aircraft Type and Base Case Configurations

We first look at the base case data (base case conditions were summarized previously in Table 3). Figure 2 plots the swath width for the 24 base case configurations against the buffer distance to 10 percent applied nonvolatile, while Figure 3 plots the swath width against maximum deposition from a single flight line.

To keep results physically motivated, we retain the physical lengths for swath width and buffer distance, rather than nondimensionalizing results by the wing spans and rotor diameters (as was done in the previous sensitivity study). Besides showing a nearly linear trend between swath width and buffer distance in Figure 2 (probably due to the use of 10 percent applied nonvolatile level), three distinct regions are identified: (1) below 50 m for the D8/46 nozzles; (2) between 50 and 100 m for the Beecomist rotary atomizers; and (3) above 130 m for the Micronair rotary atomizers. Clearly, this figure demonstrates the sensitivity of fine drops generated by the two rotary atomizers (whose VMD values were 74.5 μm for the Micronair and 125.1 μm for the Beecomist, as seen in Table 4). The importance of smaller drops will keep returning throughout this analysis.

Figure 3 retains the same three distinct regions (below 50 m, between 50 and 100 m, and above 130 m), with the realization that low levels of deposition are achieved with the rotary atomizers, and levels from 50 to 100 percent or more of active nonvolatiles are achieved with the D8/46 nozzles. The peculiar value of 234 percent was found for the Hughes 300C (NZ configuration) and suggests that the low release height of 5 m is much too low for this aircraft to achieve uniform ground deposition.

In all that follows, we will consider only the sensitivity of swath width to the variations we have undertaken here (except in several cases where the variability of buffer distance will be illuminating). Clearly, any of the other variables summarized above (maximum deposition, in-swath deposition, or buffer distance) could be determined with similar ease, with swath width being a pretty clearly defined (and understood) variable.

2. Boom Width

Boom width has long been considered an important variable to the spray community, certainly with the recent studies by the Spray Drift Task Force. The prediction developed here is shown in Figure 4.

Figure 4a shows the sensitivity of swath width for the US configuration fixed-wing aircraft. For the D8/46 nozzles, increases in boom width fraction of wing span generally increases the swath width, until a peak value (a maximum) is reached, then a decrease to full wing span. This variation can result in as much as a 50 percent increase in swath width, depending on the boom width. For the Micronair rotary atomizers, the sensitivity to boom width is much stronger, with variations above 100 percent predicted because of the smaller drop sizes (and their nonintuitive influence by the wingtip vortices). Figure 4a confirms the importance of boom width for the rotary atomizers, and to a lesser extent for the D8/46 nozzles.

Figure 4b shows the sensitivity of swath width for the US configuration helicopters. Two significant differences are seen here from the fixed-wing aircraft: (1) for the D8/46 nozzles, a simple increase in boom width increases swath width, but in this case no maximum is achieved before reaching the rotor diameter (the maximum looks to be beyond the rotor diameter, which may be why some applicators in the US use extended booms on their helicopters, but remember that as the swath width increases, so does the buffer distance, which is not good); and (2) the Beecomist rotary atomizers appear to be even more sensitive than the Micronair rotary atomizers on the fixed-wing aircraft.

Figures 4c and 4d show the NZ configurations. For the two fixed-wing aircraft, the increase in swath width with increasing boom width is similar to the D8/46 trends in the US configuration fixed-wing aircraft. However, the horizontal scale has changed here, and the sensitivity appears more dramatic than it actually is. For the helicopters the results are

even more variable, with no apparent trend (except for the peak in swath width at 0.7 boom width fraction). It would appear that the low release height washes out any increase in swath width due to increase in boom width.

These calculations suggest that D8/46 nozzles are strongly influenced by boom width (generally, a 50 percent increase in swath width when moving from 50 to 100 percent of wing span or rotor diameter), with the rotary atomizers (US configuration) and helicopters (NZ configuration) more strongly influenced (up to a 100 percent increase in swath width when moving from 50 to 100 percent of wing span or rotor diameter).

3. Release (Boom) Height

Release height is well known to have a powerful influence on drift. This sensitivity produces the results shown in Figure 5.

Figure 5a plots the US configuration fixed-wing aircraft, and demonstrates the sensitivity for the D8/46 nozzles in particular, where for the open symbols (○, ❑, Δ), an increase in release height directly correlates with an increase in swath width (and a corresponding increase in buffer distance). The Micronair rotary atomizer data is confusing, but actually shows that above 15 m the smaller drops remain aloft and do not apparently contribute to swath width (although they of course contribute to downwind drift). The higher the aircraft, the smaller the swath width becomes, as a larger portion of the drop size distribution is widely distributed downwind. The change in swath width with release height for the Micronair rotary atomizers is particularly strong below a release height of 15 m.

Figure 5b plots the results for the US configuration helicopters. Again, the same trends are evident: for the D8/46 nozzles a strong sensitivity to release height; and for the Beecomist rotary atomizers, a strong sensitivity below 20 m. Above a release height of 25 m the smaller drops from the Beecomist rotary atomizers remain aloft and do not apparently contribute to the swath width.

Figure 5c shows the very strong increase in swath width with increasing release height for the two NZ configuration fixed-wing aircraft (the buffer distance increases the same way). Figure 5d shows the corresponding correlation for the NZ configuration helicopters, where the stronger increase is for the D8/46 nozzles with the smaller VMD of 314.0 μm, and the lesser increase is from the larger VMD of 613.0 μm.

4. Spraying Speed

Spraying speed is seen from Eq 5 to help determine the wingtip vortex strength. Thus, an increase in spraying speed can be expected to decrease vortex strength and therefore increase swath width. This effect, however, will depend upon release height and drop size, and could increase or decrease deposition in the near field. Changes in spraying speed should also modify the drop size distribution from the nozzles (because shear across the spray exit stream increases with increasing spraying speed), but this effect is not included in the first part of this sensitivity. Figure 6 gives the results.

Figure 6a shows the variation of swath width with spraying speed (the same trends are present for buffer distance) for the US configuration fixed-wing aircraft. For the D8/46 nozzles swath width shows a slight decrease with increasing spraying speed, while there is a dramatic increase in swath width with increasing spraying speed for the Micronair rotary atomizers. The increase in spraying speed decreases the vortex strength, allowing the

smaller drop sizes to deposit downwind closer to the aircraft, rather than remaining trapped aloft. The effect of spraying speed on swath width was not anticipated for the smaller drop sizes, and is an important finding of this sensitivity study.

Figure 6b presents the results for the US configuration helicopters. Again, the slight decrease of swath width with increasing spraying speed is evident in the D8/46 nozzles, with more sensitivity of swath width present for increasing spraying speed for the Beecomist rotary atomizers. The effect of spraying speed on swath width for rotary atomizers is more than previously thought.

Figure 6c shows that the NZ configuration fixed-wing aircraft behave the expected way, with a decrease in swath width coming with an increase in spraying speed). Figure 6d for the NZ configuration helicopters shows similar results.

An additional spraying speed study was undertaken by including three additional drop size distributions measured at three distinct spraying speeds. The results are shown in Figure 7 (US configuration only), and show the same decrease in swath width with increase in spraying speed (especially for the helicopter) as discussed above.

5. Aircraft Weight

The effect of aircraft weight sensitivity is shown in Figure 8.

Figure 8a plots the sensitivity of the US configuration fixed-wing aircraft. There is a very slight increase in swath width with increase in aircraft weight. The sensitivity on the Micronair rotary atomizers swath width is far more dramatic (above 0.75 the larger aircraft weight increases the vortex strength and keeps the spray material trapped in the vortices, permitting only the larger drops to hit the surface).

Figure 8b shows the corresponding US configuration helicopter sensitivity to aircraft weight. The sensitivity for the D8/46 nozzles is again slight, while the Beecomist rotary atomizer sensitivity is significant. The Bell JetRanger III demonstrates some anomalous behavior, but the other two helicopters clearly show a significant trend of increasing swath width with increasing aircraft weight. The opposite trend is seen for the Micronair rotary atomizers (Figure 8a) and is probably tied to the drop sizes emitted by the Micronair. The larger drops from the Beecomist are probably captured by the vortices and driven into the ground, generating larger swath widths at higher aircraft weights. These trends demonstrate the surprising difference between aircraft and nozzle type, and were not uncovered in the previous sensitivity study, but are consistent with our physical interpretation. What is suggested here, I believe, is that heavier aircraft tend to push more spray material downward toward the surface (anticipated by a higher value of wingtip vortex strength from Eq 5), but smaller drop sizes are more affected. Larger drop sizes (as for the D8/46) all deposit on the surface, no matter what the aircraft weight.

Figure 8c plots the NZ configuration fixed-wing aircraft, and shows a consistent increase in swath width with an increase in aircraft weight. Figure 8d plots the NZ configuration helicopters, and shows the sensitivity evident by the helicopters at their low release height. These figures suggest that aircraft weight effects are also a function of release height: the D8/46 nozzles slightly increase swath width with increasing aircraft weight in the US configuration (15 m release height), and more dramatically increase swath width with increasing aircraft weight in the NZ configuration (5 m release height). Higher release heights may mask the effect of changes in aircraft weight.

6. Wind Direction

It is anticipated that wind direction (taken relative to flight direction in all that follows) will contribute strongly to changes in swath width. Figure 9 shows these effects.

Figure 9a for the US configuration fixed-wing aircraft shows that swath width is marginally affected in D8/46 nozzles by wind direction (buffer distance effect is stronger, increasing by a factor of four for increase in wind direction from 0 deg to 90 deg). The Micronair rotary atomizer results, with smaller drop sizes, produce a more dramatic effect on both swath width and buffer distance. This plot (Figure 9a) is for swath width verses buffer distance, to recover the dramatic effects included with changes in wind direction, primarily the downwind drift of the smaller drops generated by the rotary atomizers. When the wind changes direction from along the flight line (0 deg) to perpendicular to it (90 deg), the character of the deposition changes accordingly. These results also indicate that one variable (swath width) may be relatively insensitive, while another (buffer distance) is strongly affected.

Figure 9b for the US configuration helicopters shows similar sensitivity to the Beecomist rotary atomizers (a strong influence of wind direction to both swath width and buffer distance), but now some effect to the D8/46 nozzles is seen as well. Both Figures 9a and 9b show clearly that wind direction is a strong parameter in sensitivity.

Figure 9c shows the wind direction sensitivity for the NZ configuration fixed-wing aircraft. The behavior is quite smooth for the Cessna Ag Wagon, but more erratic for the Fletcher. Figure 9d shows the sensitivity for NZ configuration helicopters. Generally, the 0 deg wind direction is positioned near the bottom of the plot, and moves toward 90 deg at the top. There is a trend toward reducing swath width with increasing wind direction (as before, relative to flight direction) for the helicopters for the lower VMD sprays, while the higher VMD sprays tend to be more variable.

7. Wind Speed

Figure 10 presents the results for wind speed sensitivity.

Figure 10a gives the results for the US configuration fixed-wing aircraft. For the D8/46 nozzle increasing wind speed increases swath width, but for the Micronair rotary atomizers, an opposite trend is seen in the figure. It would appear that the smaller drop sizes are spread out more downwind, creating the effect of reducing the swath width. Buffer distance always increases with increasing wind speed, even for the smaller drop sizes.

Figure 10b gives the US configuration results for helicopters. The results are very similar to the fixed-wing aircraft, but with a more dramatic increase for the D8/46 nozzles, and less dramatic decrease for the Beecomist rotary atomizers.

Figures 10c and 10d give the results for the NZ configuration fixed-wing aircraft and helicopters, respectively. The variation of swath width with wind speed for the fixed-wing aircraft is not very dramatic, while for the helicopters, all of the curves show that swath width tends to increase with an increase in wind speed (the smaller drop size effect is not present here, probably because of the lower release height in the NZ configuration (5 m) compared with the US configuration (15 m).

8. Nonvolatile Fraction

As nonvolatile fraction increase, drops will remain larger and deposit closer to the aircraft flight line. Figure 11 give the results. The D8/46 nozzle results (US configuration) are insensitive to increase in nonvolatile fraction (this feature may not hold true with higher release heights), while the rotary atomizer results show a slight decrease in swath width with increasing nonvolatile fraction as spray material deposits closer to the aircraft (Figures 11a and 11b). For the NZ configurations Figures 11c and 11d show that the D8/46 nozzles are relatively insensitive to increases in nonvolatile fraction as well. Overall, Figure 11 shows that there is very little effect to swath width due to nonvolatile fraction (this result had been observed in the previous sensitivity study as well).

9. Wet Bulb Temperature Depression

Ambient temperature and relative humidity sensitivity can be combined into the single variable wet bulb temperature depression ΔT_{wb}. The relationship between ambient temperature and relative humidity was previously shown in Figure 1, where it may be seen that temperature and relative humidity changes can be nearly linear with ΔT_{wb}, depending upon the values of temperature and relative humidity. A change in wet bulb depression can be accomplished in an infinite number of ways, depending on how temperature and relative humidity actually change. If ΔT_{wb} is an important influence on swath width (as detailed here), then it is reasonable to assume that temperature and relative humidity are just as important. Figure 12 presents the sensitivity results.

Figure 12a shows the results for the US configuration fixed-wing aircraft. As in the last sensitivity study, the effect on evaporation is found to be quite minimal for large drop size distributions (such as the D8/46 nozzle types used here), but is more important for very small ΔT_{wb} values for the smaller drop sizes (generated by the Micronair rotary atomizers), until evaporation strips all of the volatile spray material away; then a fairly constant swath width is obtained. Swath width may actually decrease slightly with ΔT_{wb} at large values of wet bulb depression because very rapid evaporation quickly creates smaller drops, and they in turn travel farther downwind before depositing. These effects were not included in the previous sensitivity study because we were not looking in this detail.

Figure 12b shows a similar effect for the US configuration helicopters.

Figures 12c and 12d give the NZ configuration results, which are effectively insensitive to ΔT_{wb} (their corresponding buffer distances increase somewhat with increase in wet bulb depression).

Buffer distance, however, is more dramatically a function of ΔT_{wb}, as seen in Figure 13 for the twelve aircraft configurations. From this figure it is clear that wet bulb depression is an important sensitivity variable for downwind drift. The previous sensitivity study concluded that temperature and relative humidity changes were not important; the present results suggest that our previous sensitivity study did not examine the downwind drift issue with as much detail as we do here. Most especially, smaller drops are more dramatically affected by a change in ΔT_{wb} (comparing the rotary atomizer buffer distances

in Figures 13a and 13b, and the VMD = 314.0 μm buffer distances in Figures 13c and 13d).

10. Nozzle Type

Nozzle type sensitivity was explored by changing drop size distribution, referenced to VMD. Figure 14 plots the results for swath width (buffer distance behaves the same way as swath width).

Figure 14a gives the results for the US configuration fixed-wing aircraft, a strong effect replicated by the three aircraft considered. Clearly, for drop size distributions with VMD below 200 μm, swath width dramatically increases with decreasing VMD. Figure 14b presents a similar result for the US configuration helicopters.

Figures 14c and 14d present similar results for the NZ configuration aircraft. The swath widths are smaller because the release height is lower.

11. Specific Gravity

Specific gravity effects for four aircraft are given in Figure 15. Figure 15a shows the results for the Ayres Turbo Thrush, again showing that smaller drop sizes show decreases in swath width with increases in specific gravity. These results confirm the importance of specific gravity for smaller drop sizes, as determined in the previous sensitivity study. Figure 15b shows similar results for the Bell JetRanger III (US configuration); Figure 15c for the Fletcher; and Figure 15d for the Bell JetRanger III (NZ configuration).

An additional specific gravity sensitivity was also performed, by examining the actual effect of nonunity specific gravity through several nozzles on the two US configuration aircraft. These results are compared with water results in Figure 16, where it may be seen that an increase in specific gravity causes a decrease in swath width. In one instance the decrease was 20 percent, a significant effect.

12. Release Height and Wind Speed and
13. Release Height, Temperature and Relative Humidity

These two sensitivities create a large matrix of results that quantify the dramatic increase in swath width and buffer distance for increases in release height, wind speed, and VMD. These variations will form the basis for the Training Module in SpraySafe Manager and the Near-Wake Sensitivity Library in FSCBG. Variations include:

1. Three aircraft (Ayres Turbo Thrush, Bell JetRanger III -- both configurations -- and Fletcher);
2. Eight drop size distributions;
3. Release height; and
4. One other independent variable (either wind speed or wet bulb temperature depression).

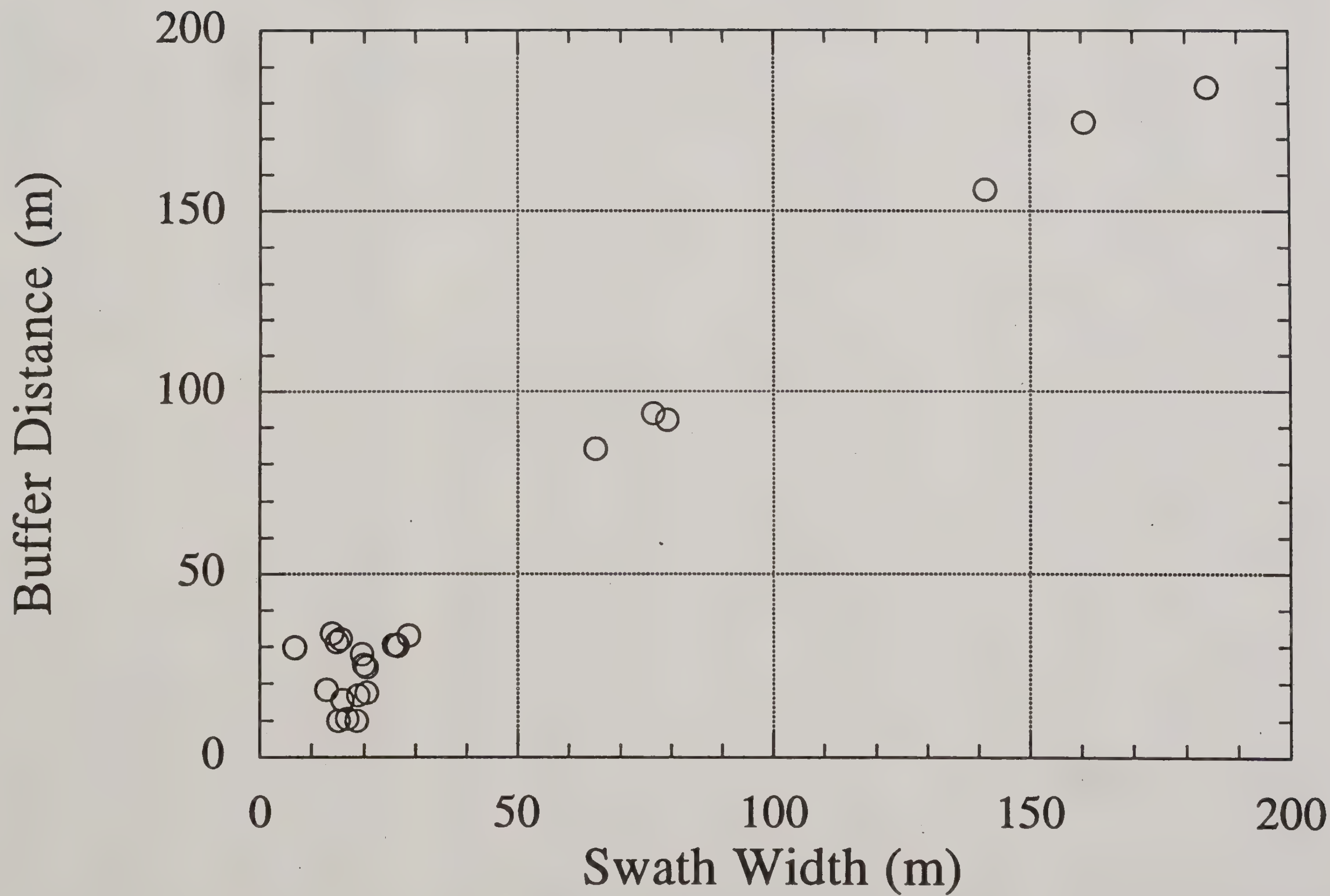

Figure 2. Display of the variability of swath width and buffer distance in the 24 base case data configurations (each O represents one of the 24 FSCBG calculations).

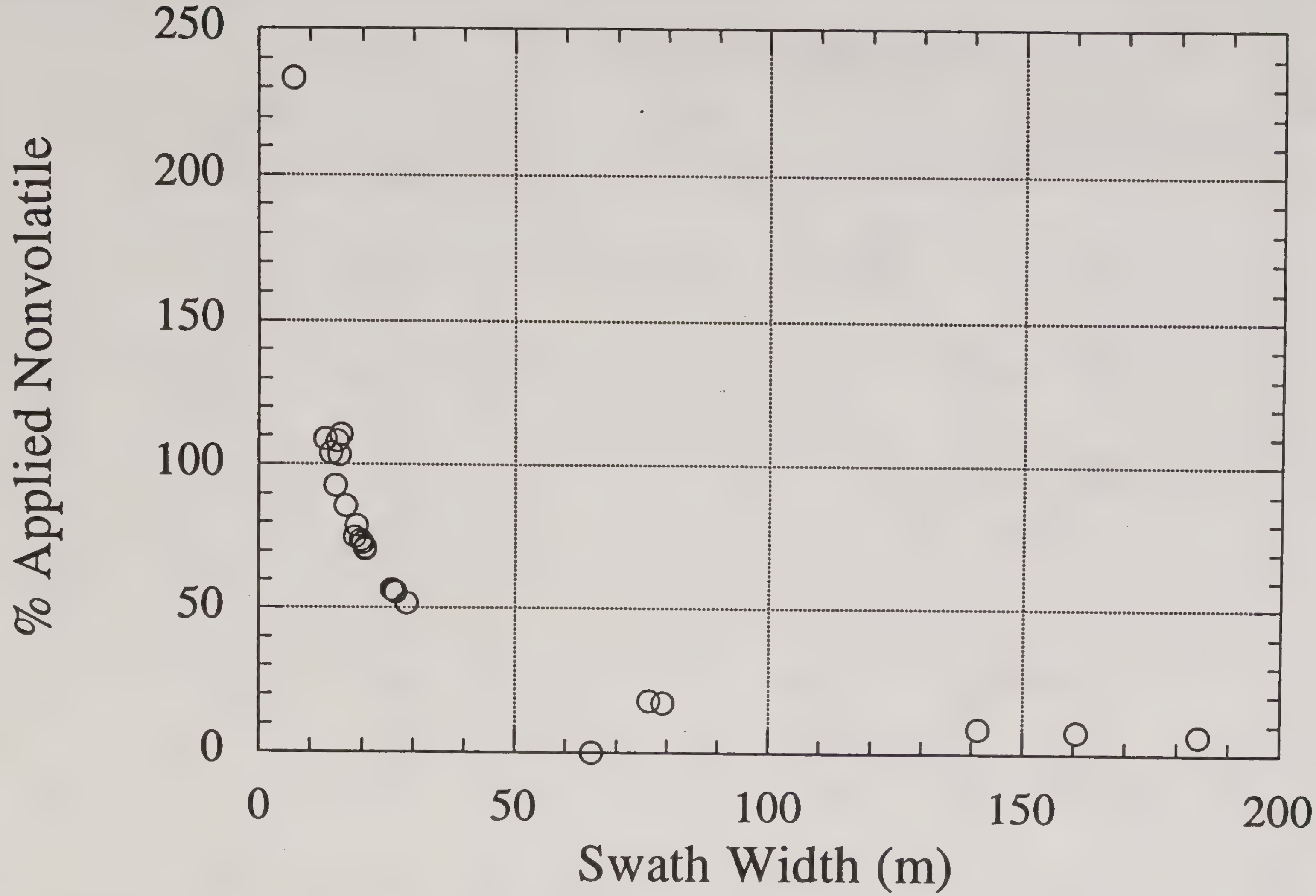

Figure 3. Display of the variability of swath width and percent applied nonvolatile from a single flight line, in the 24 base case data configurations (each O represents one of the 24 FSCBG calculations).

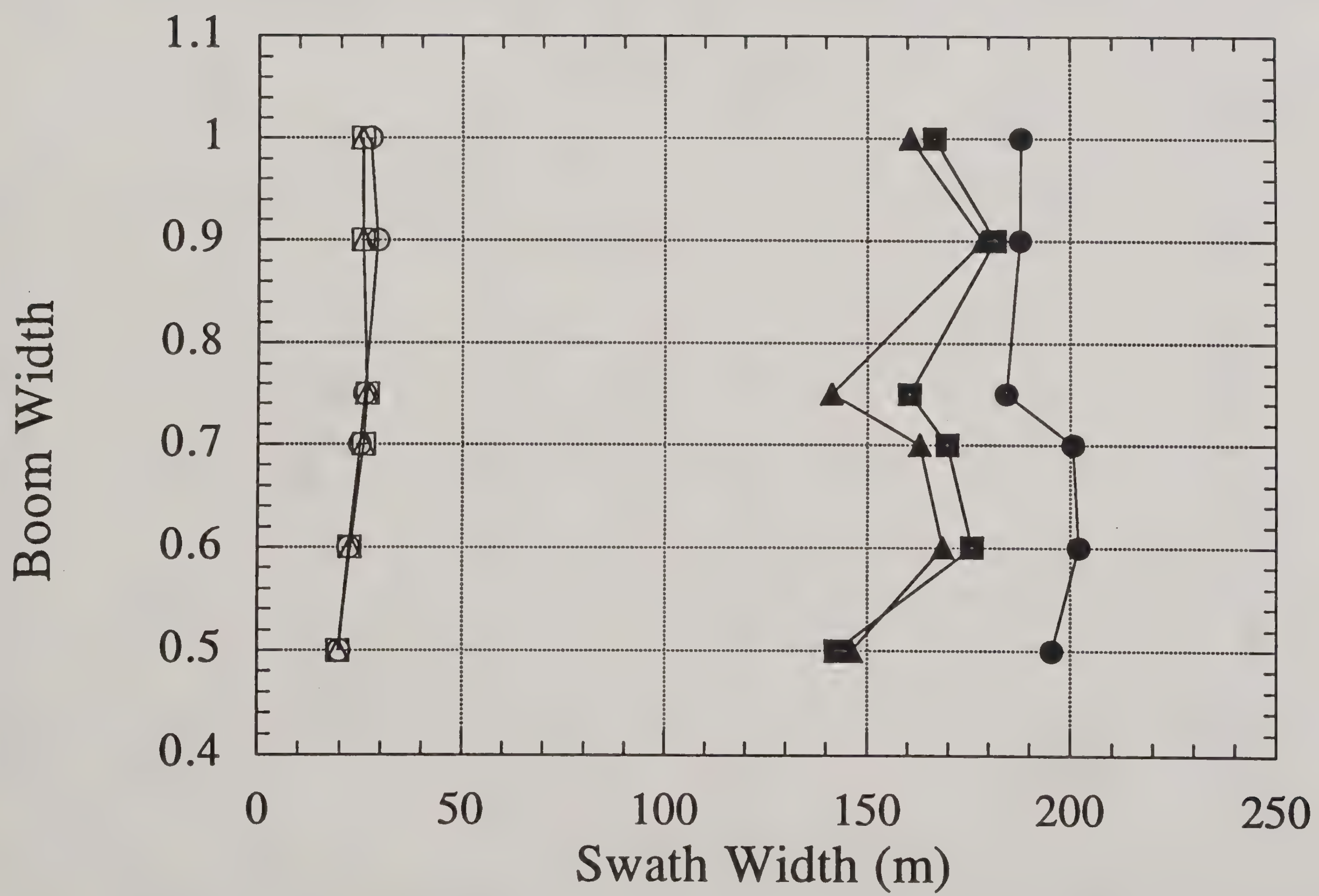

Figure 4a. Sensitivity of swath width to boom width fraction (where 1 equals the fixed-wing aircraft wing span). The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

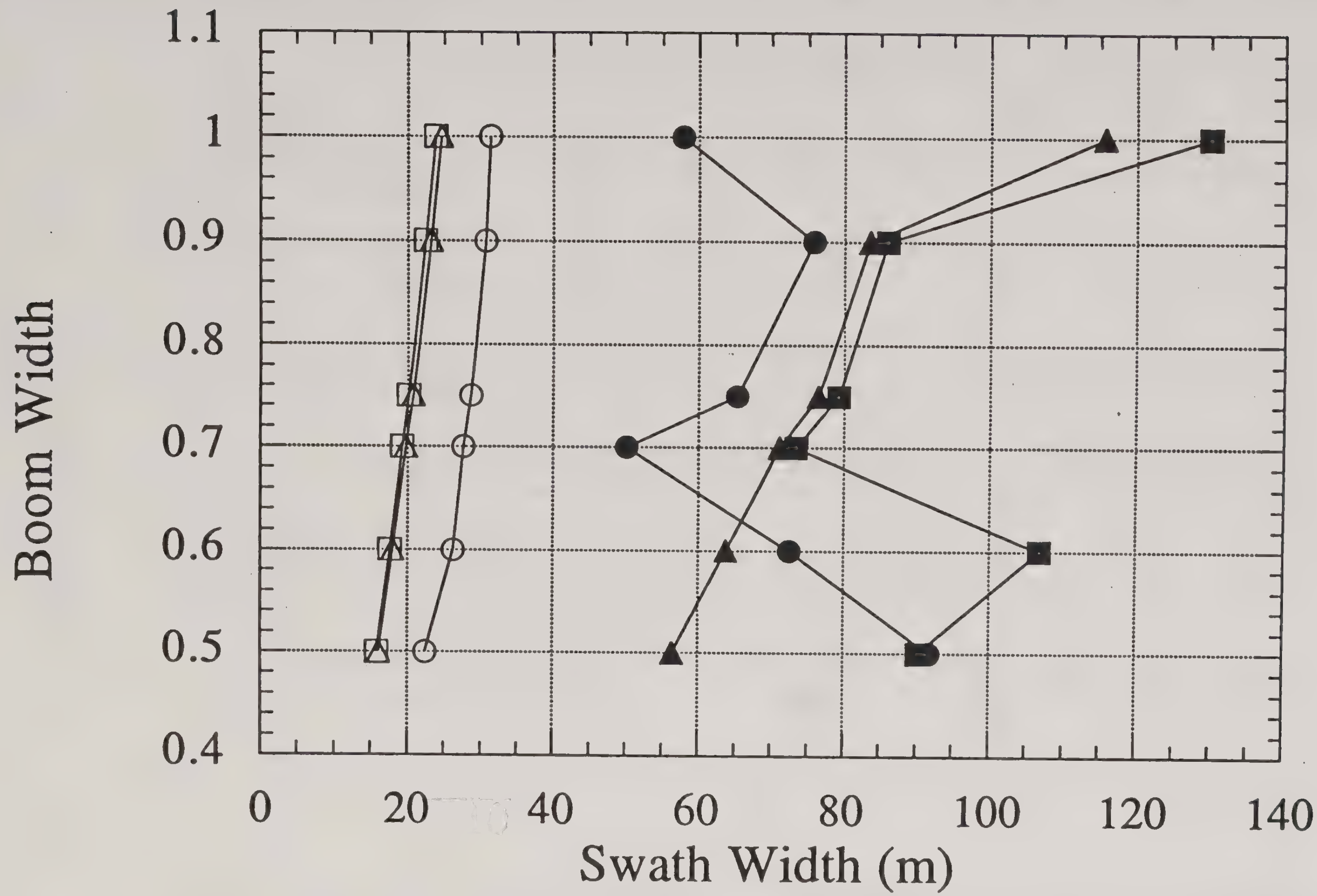

Figure 4b. Sensitivity of swath width to boom width fraction (where 1 equals the helicopter rotor diameter). The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

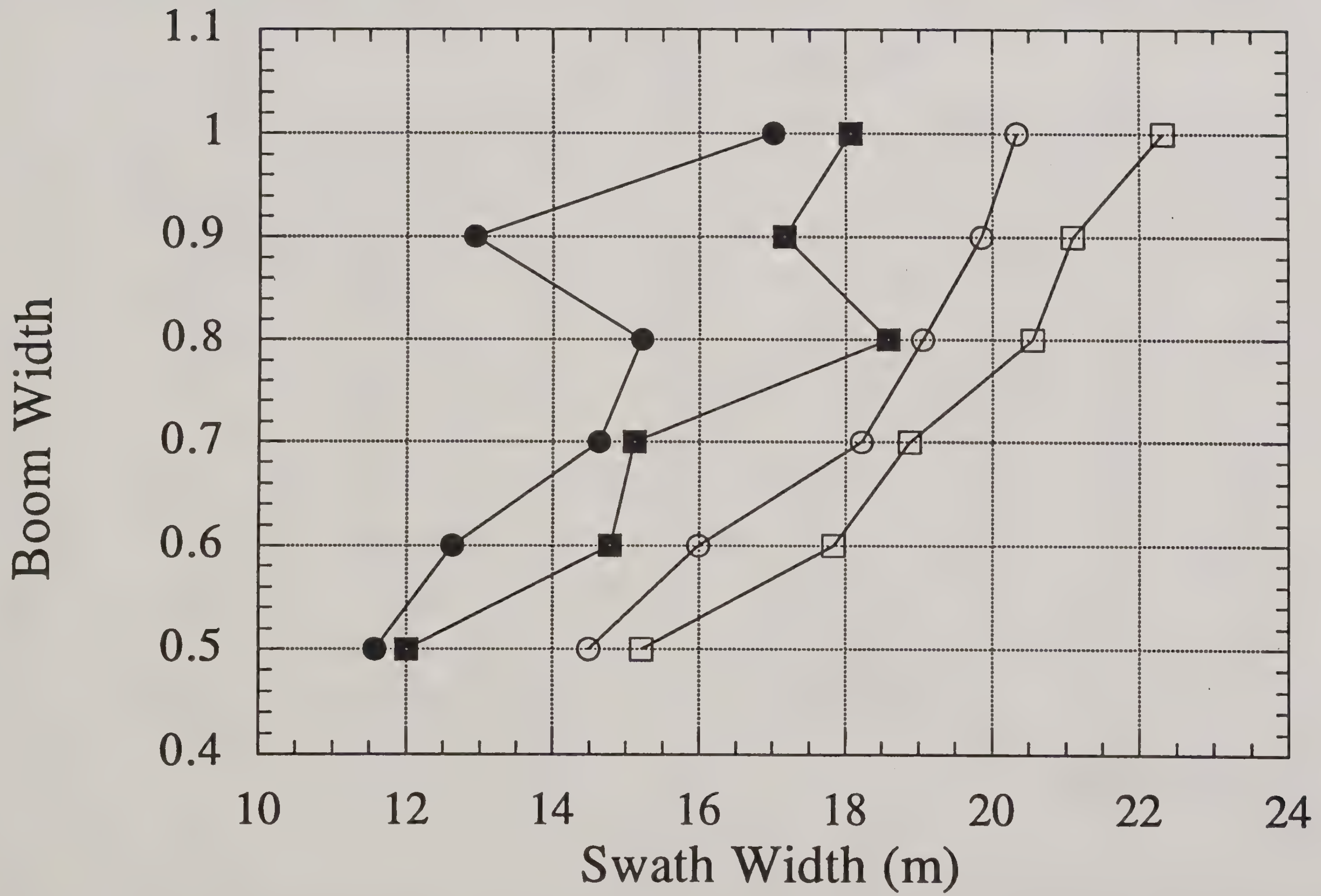

Figure 4c. Sensitivity of swath width to boom width fraction (where 1 equals the fixed-wing aircraft wing span). The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

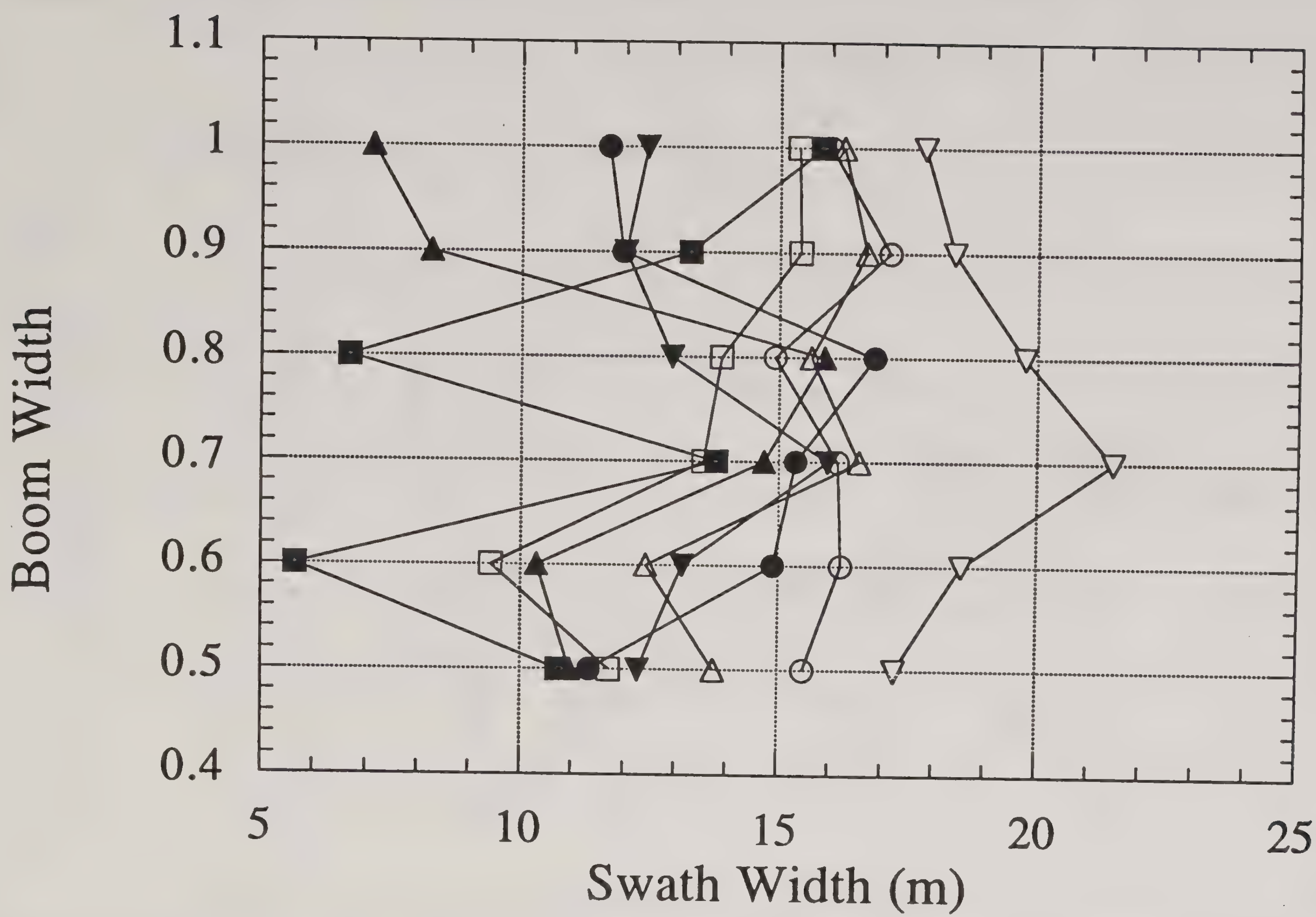

Figure 4d. Sensitivity of swath width to boom width fraction (where 1 equals the helicopter rotor diameter). The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

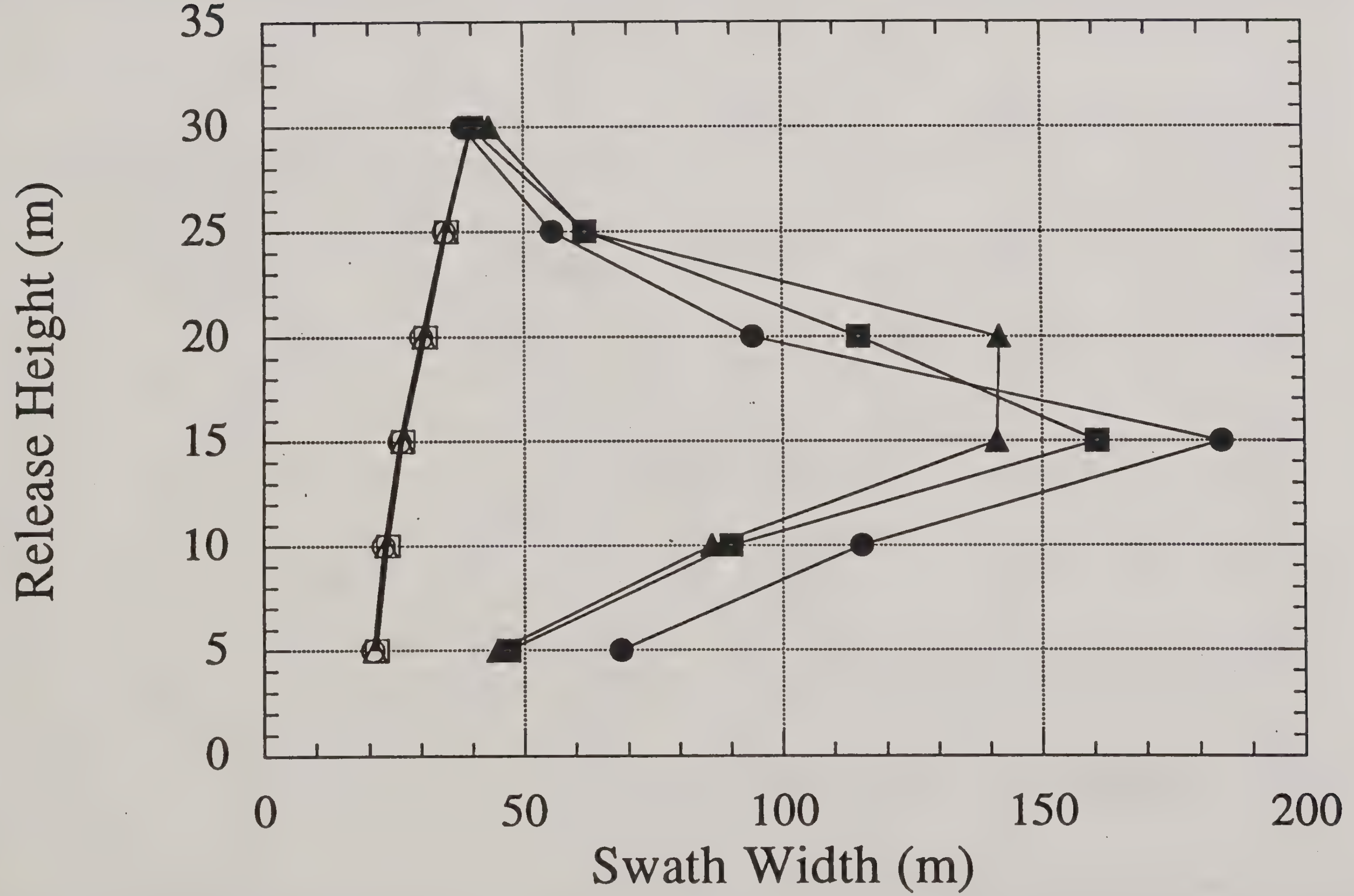

Figure 5a. Sensitivity of swath width to release height. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

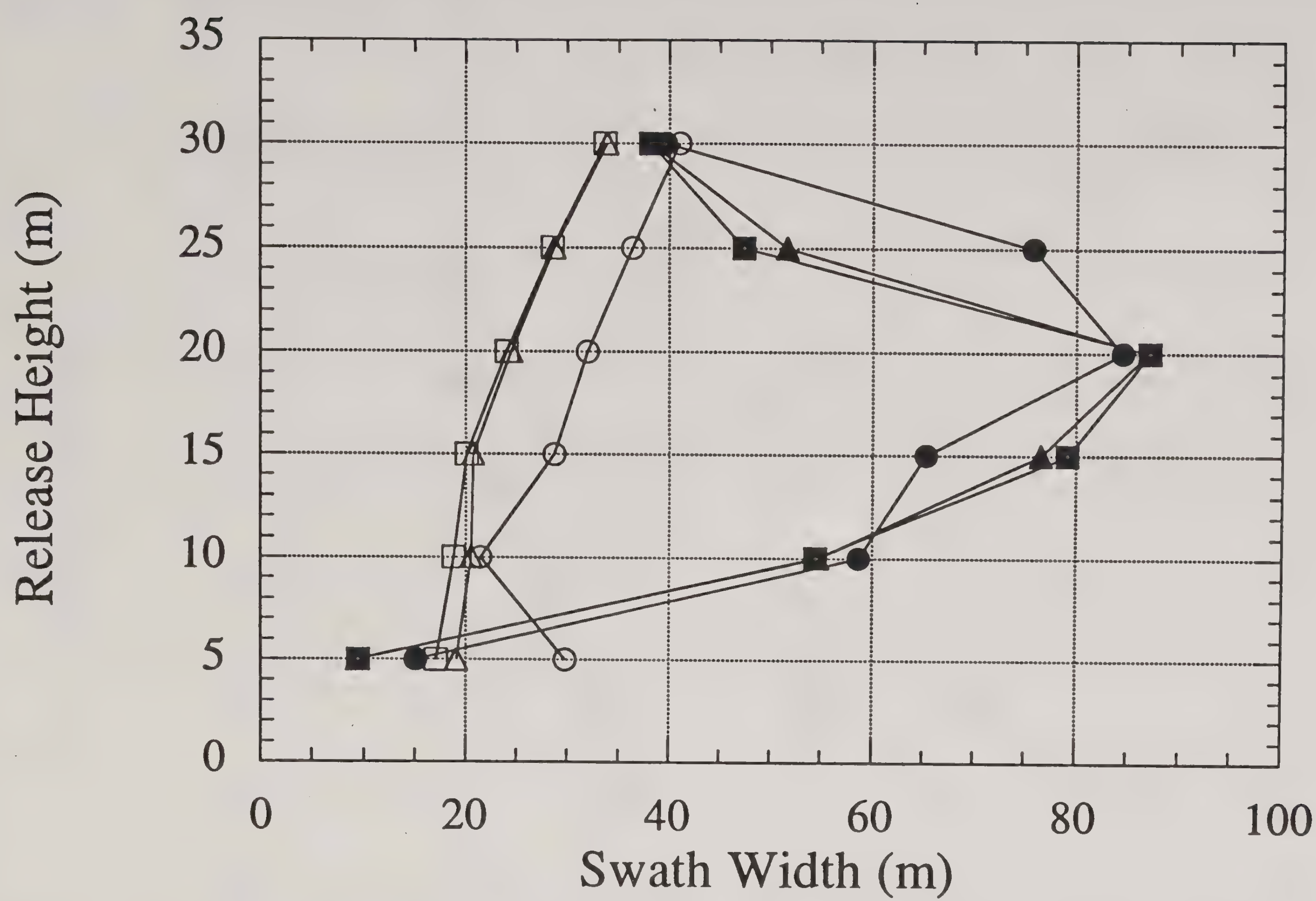

Figure 5b. Sensitivity of swath width to release height. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

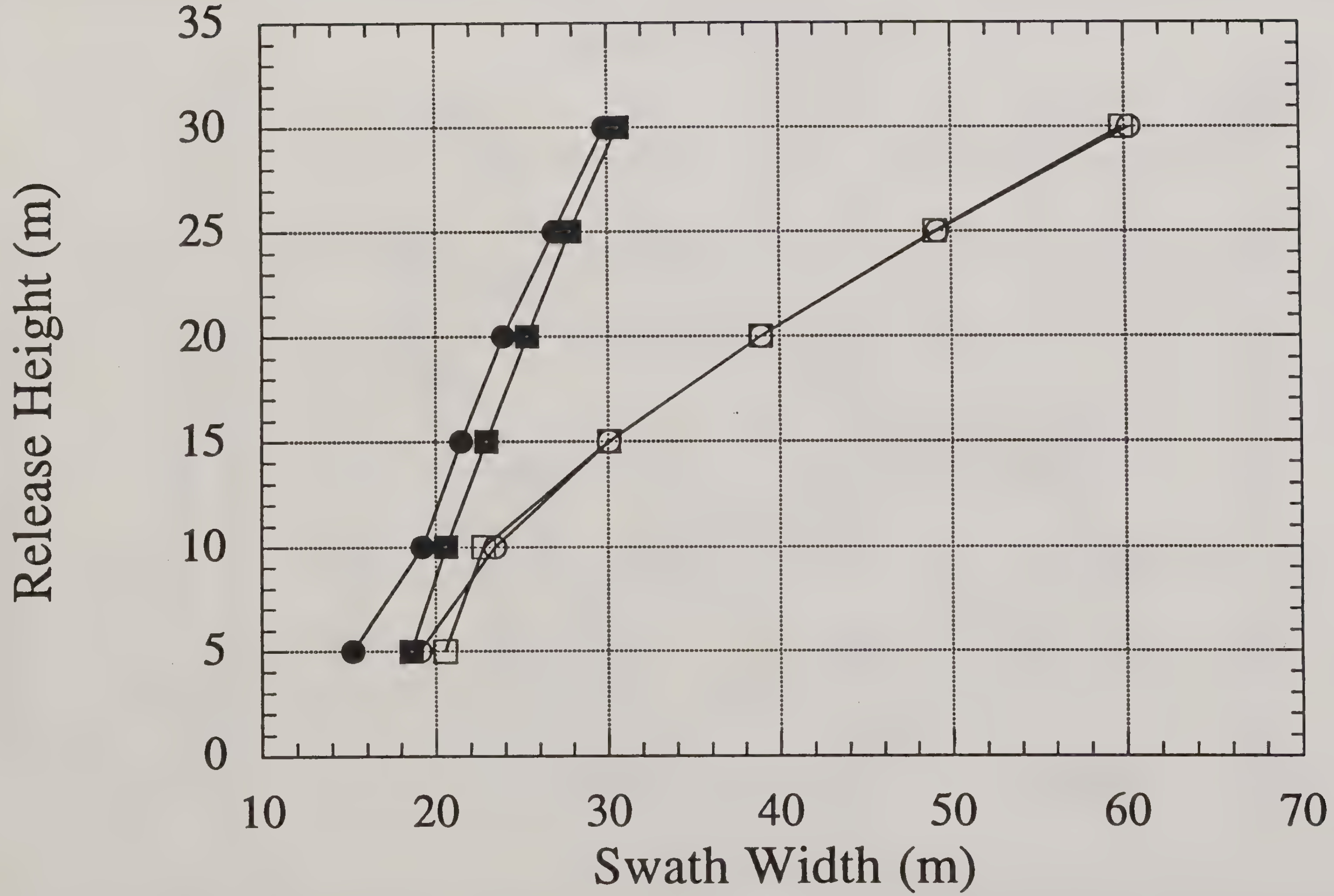

Figure 5c. Sensitivity of swath width to release height. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

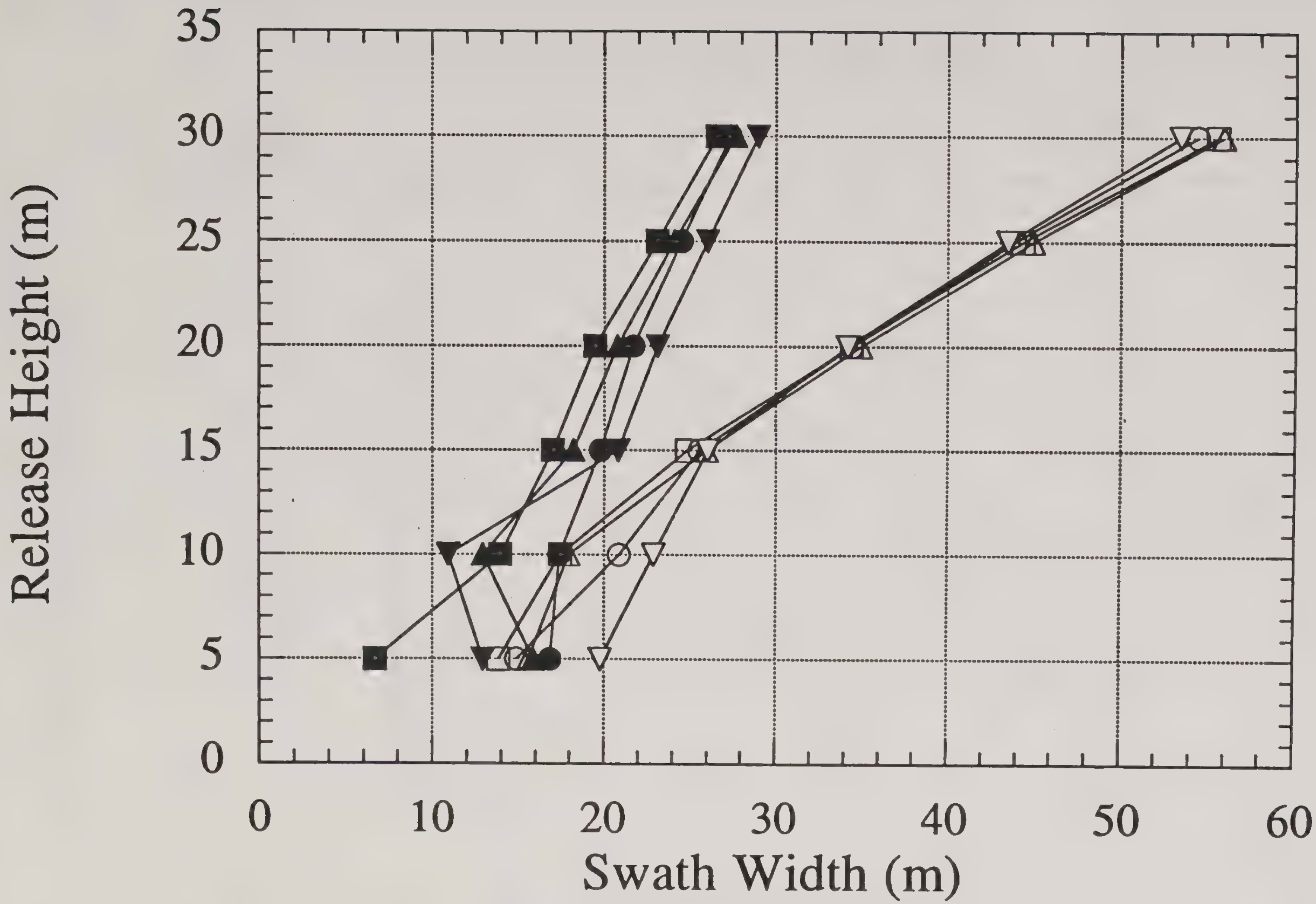

Figure 5d. Sensitivity of swath width to release height. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (△); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (▽); and Squirrel with D8/46 nozzles and larger VMD (▼).

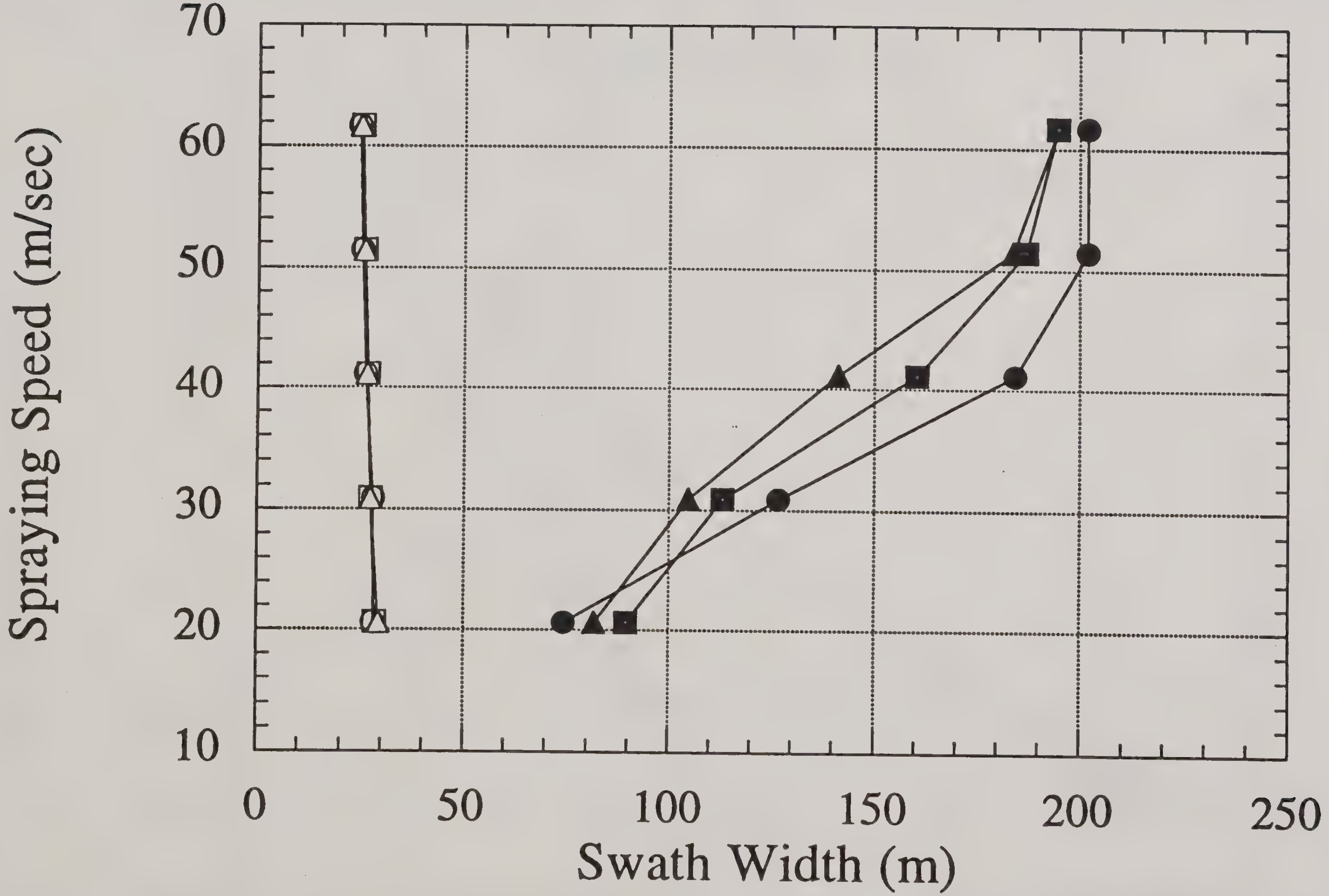

Figure 6a. Sensitivity of swath width to spraying speed. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

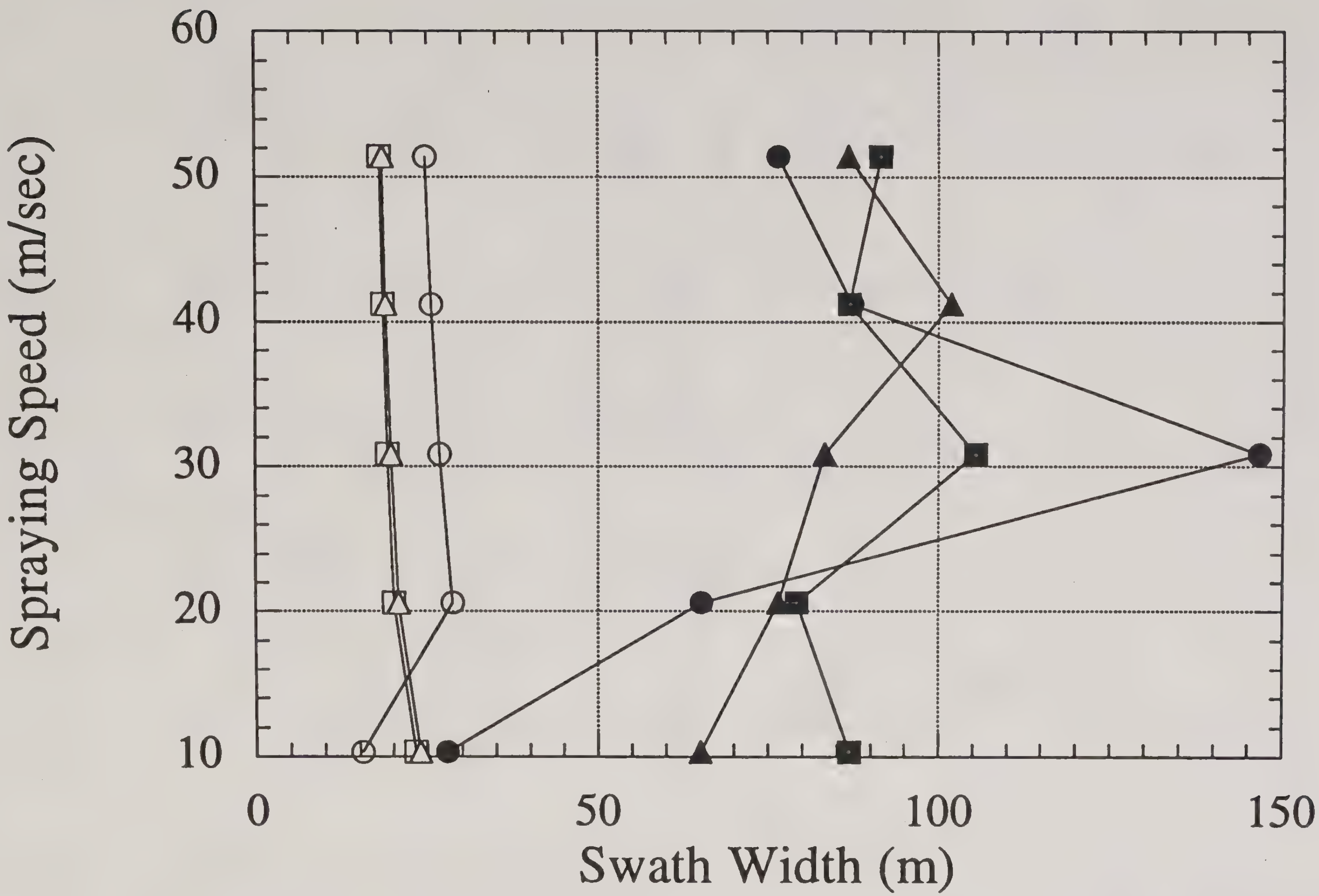

Figure 6b. Sensitivity of swath width to spraying speed. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

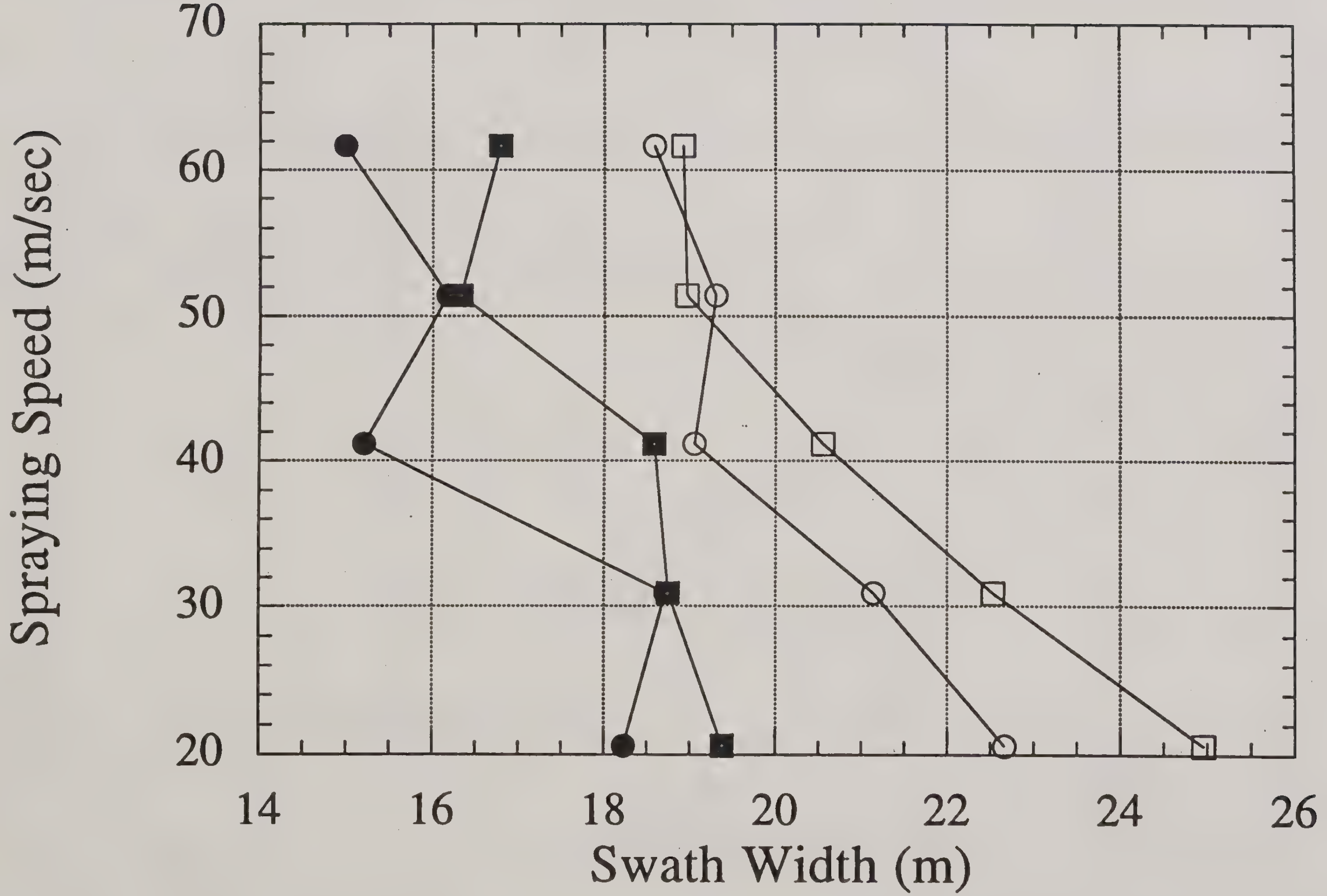

Figure 6c. Sensitivity of swath width to spraying speed. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

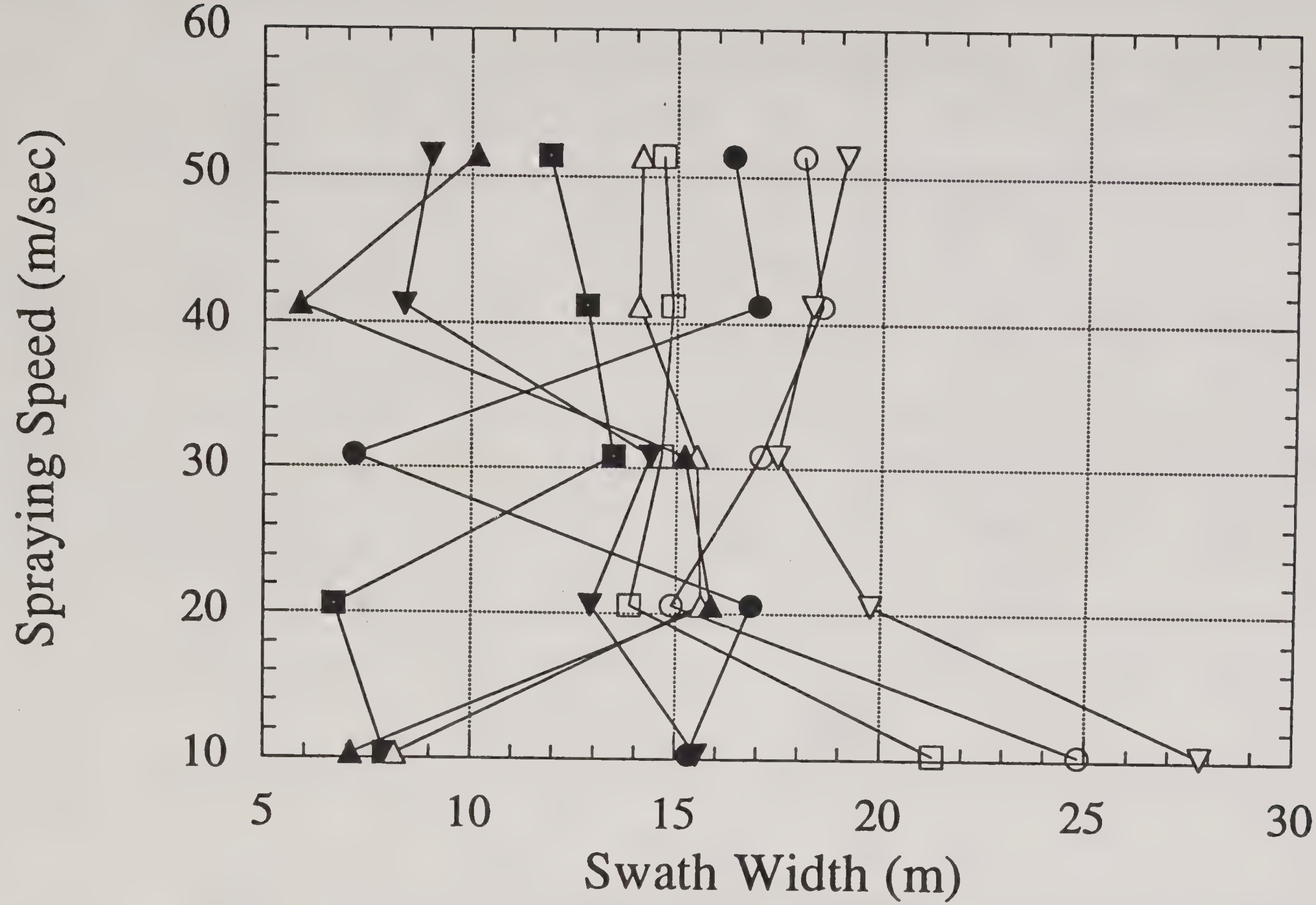

Figure 6d. Sensitivity of swath width to spraying speed. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

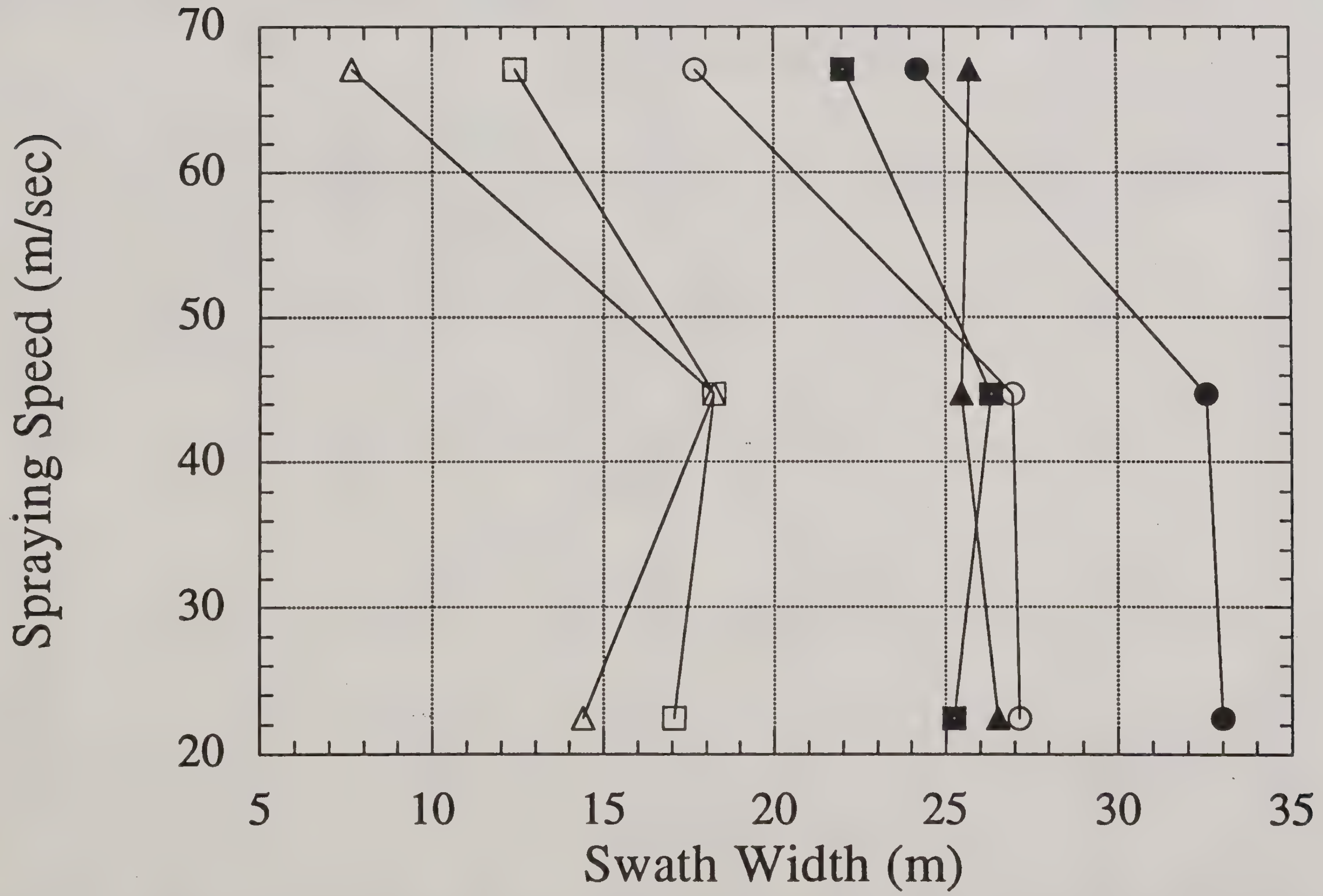

Figure 7. Further sensitivity of swath width to spraying speed. The configurations represented are: Bell JetRanger III with D8 jet nozzles (○), with D8/46 nozzles (□), with RD-7 nozzles (Δ); and Ayres Turbo Thrush with D8 jet nozzles (●), with D8/46 nozzles (■), with RD-7 nozzles (▲).

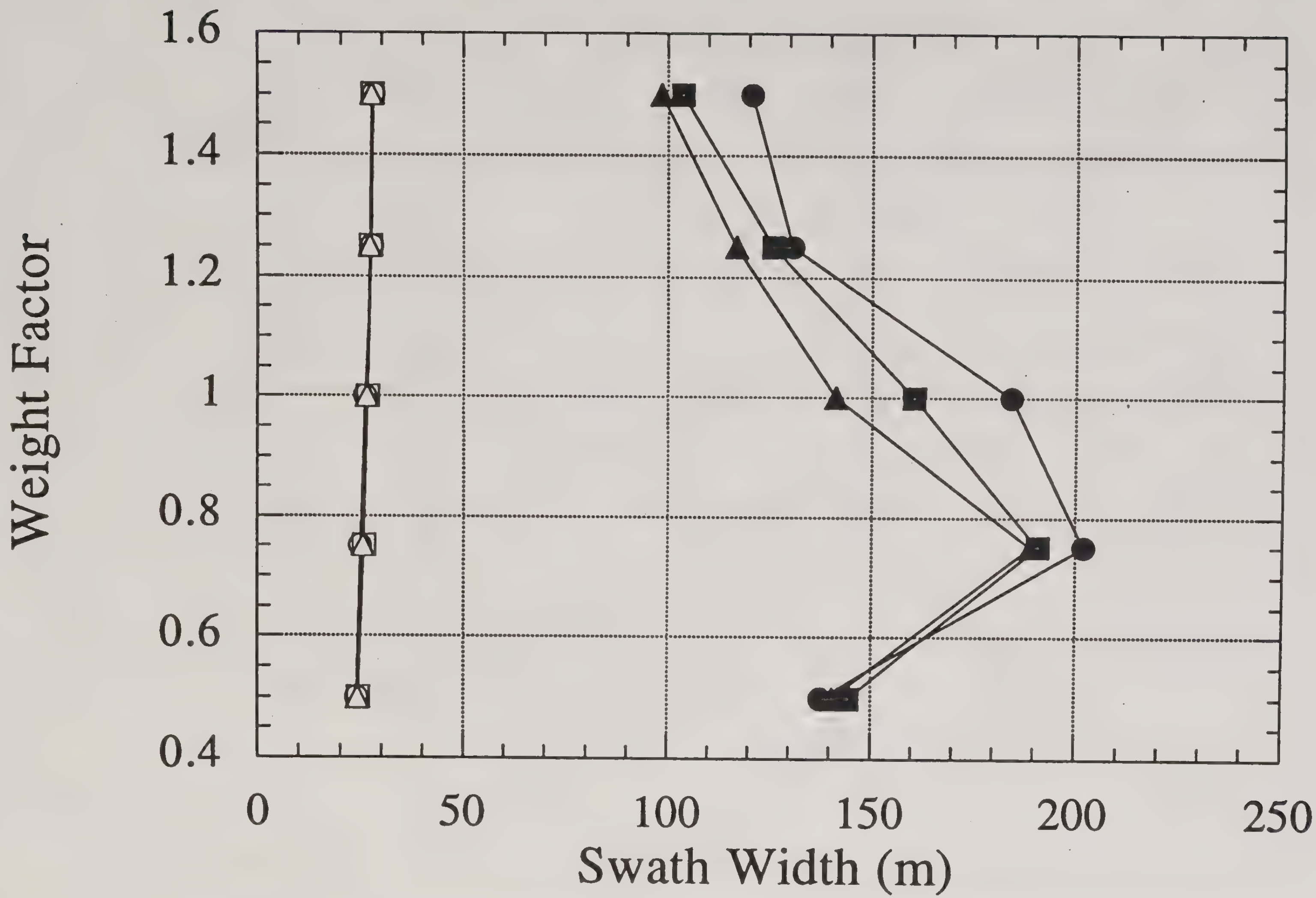

Figure 8a. Sensitivity of swath width to aircraft weight fraction (where 1 equals the default weight of the fixed-wing aircraft). The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

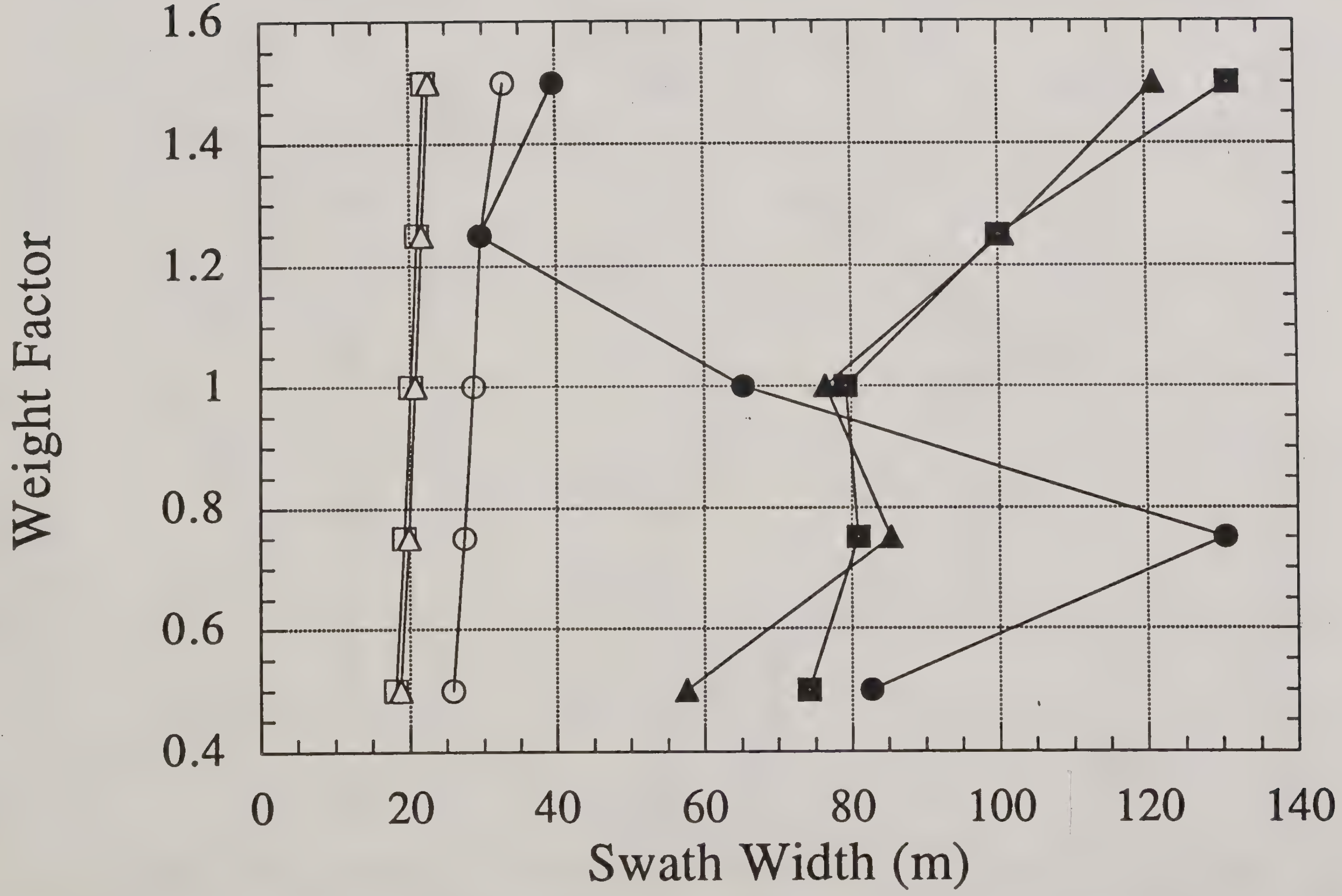

Figure 8b. Sensitivity of swath width to aircraft weight fraction (where 1 equals the default weight of the helicopter). The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

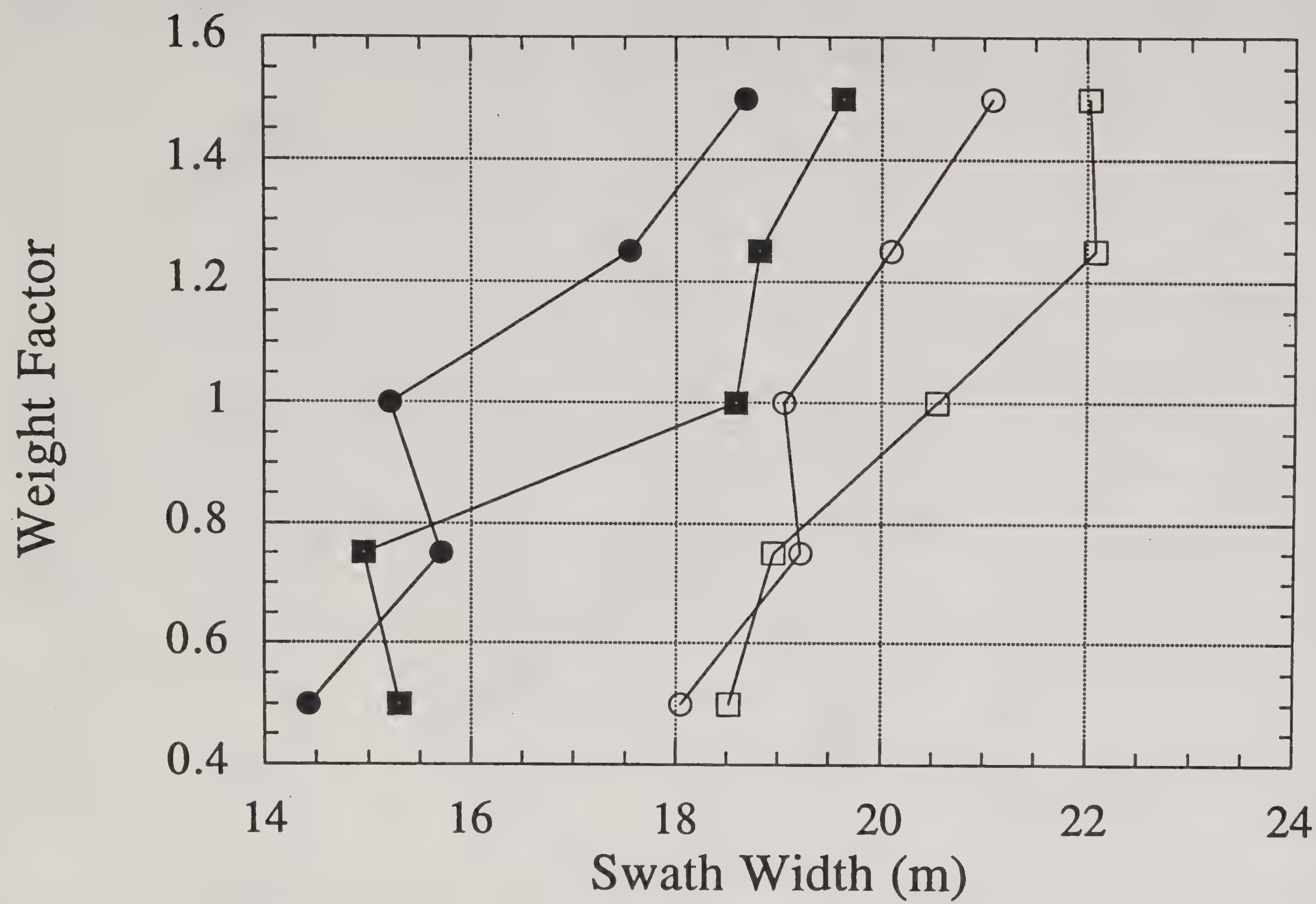

Figure 8c. Sensitivity of swath width to aircraft weight fraction (where 1 equals the default weight of the fixed-wing aircraft). The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

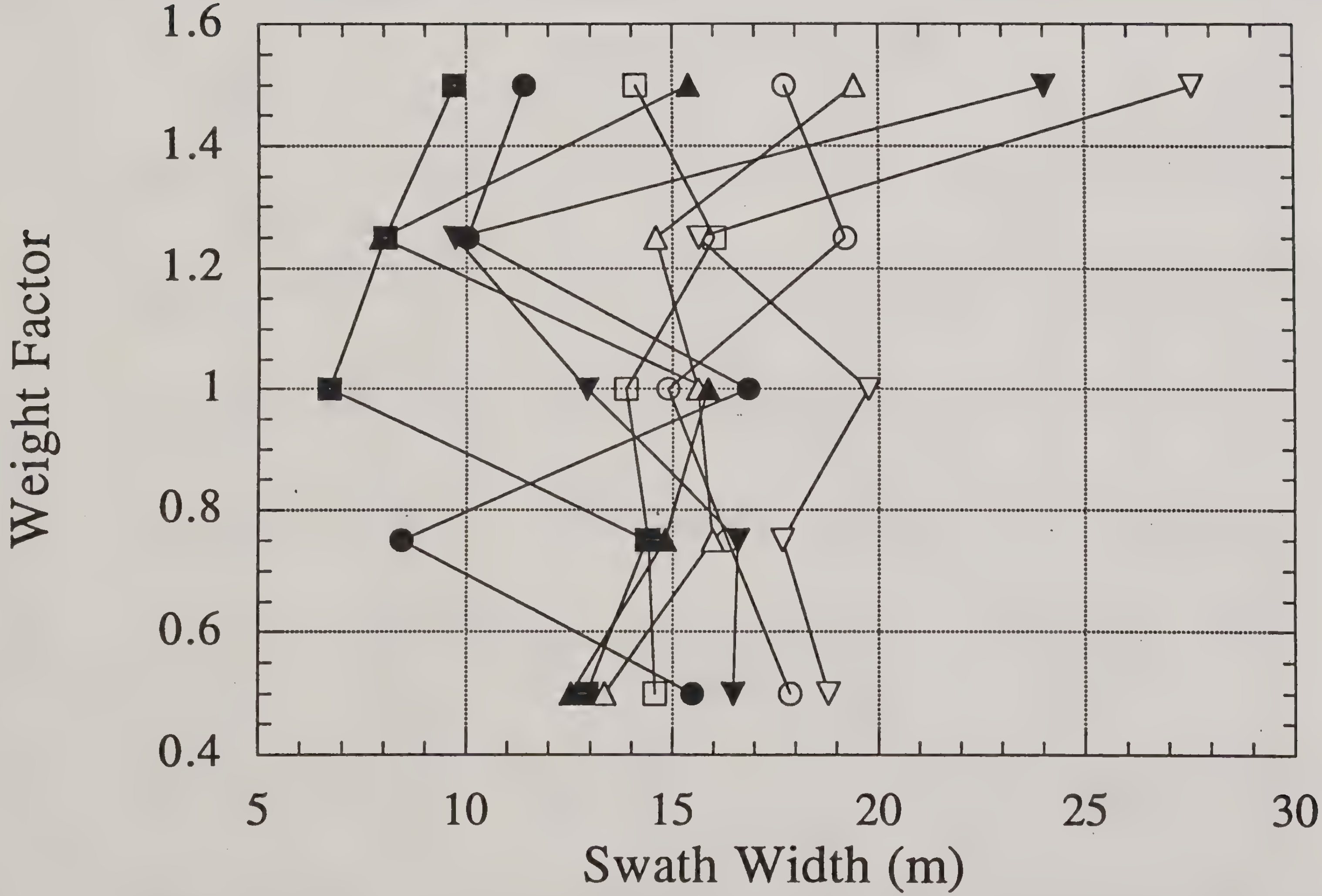

Figure 8d. Sensitivity of swath width to aircraft weight fraction (where 1 equals the default weight of the helicopter). The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

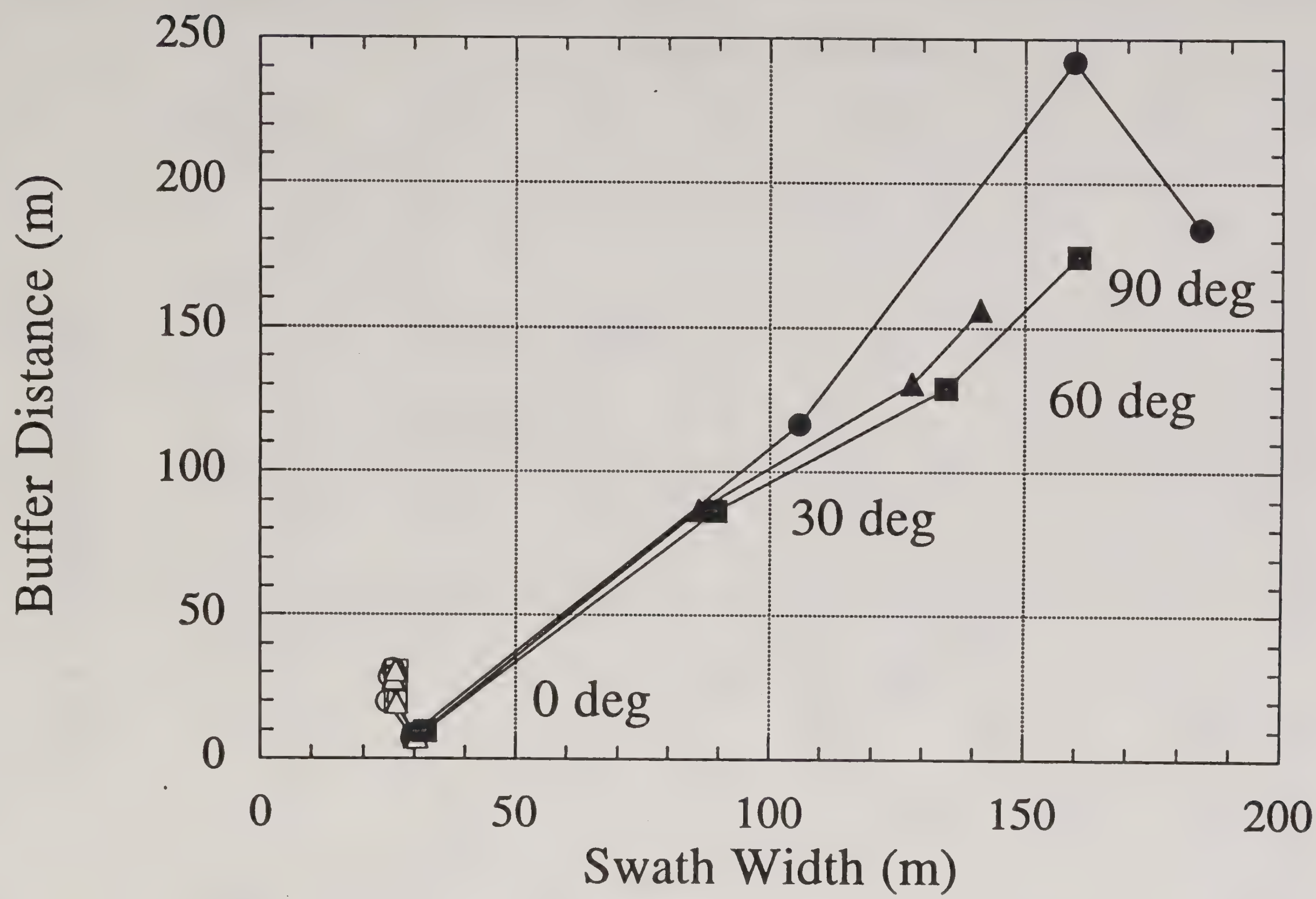

Figure 9a. Sensitivity of swath width and buffer distance to wind direction (0 to 90 deg relative to the aircraft flight line). The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

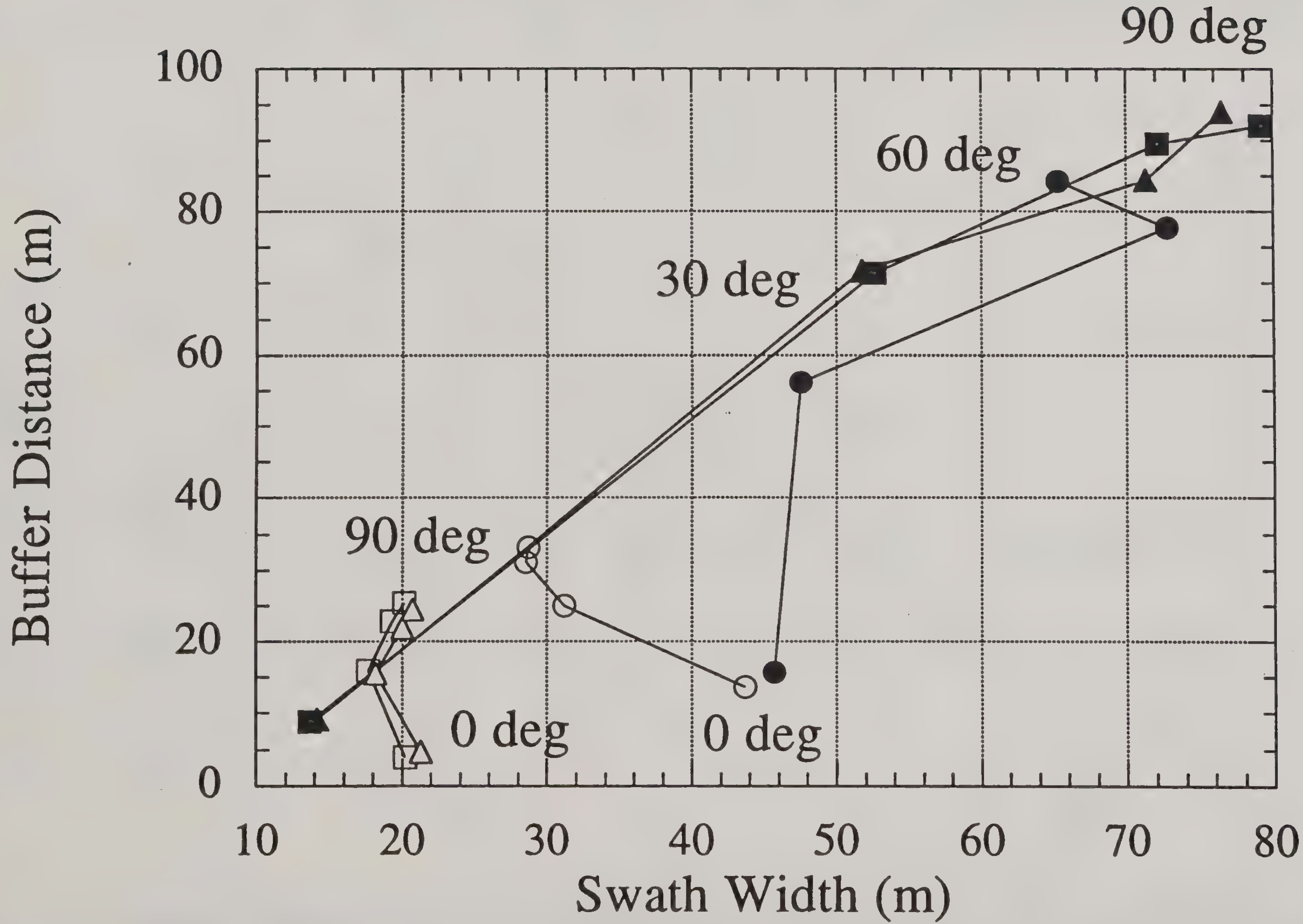

Figure 9b. Sensitivity of swath width and buffer distance to wind direction (0 to 90 deg relative to the aircraft flight line). The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

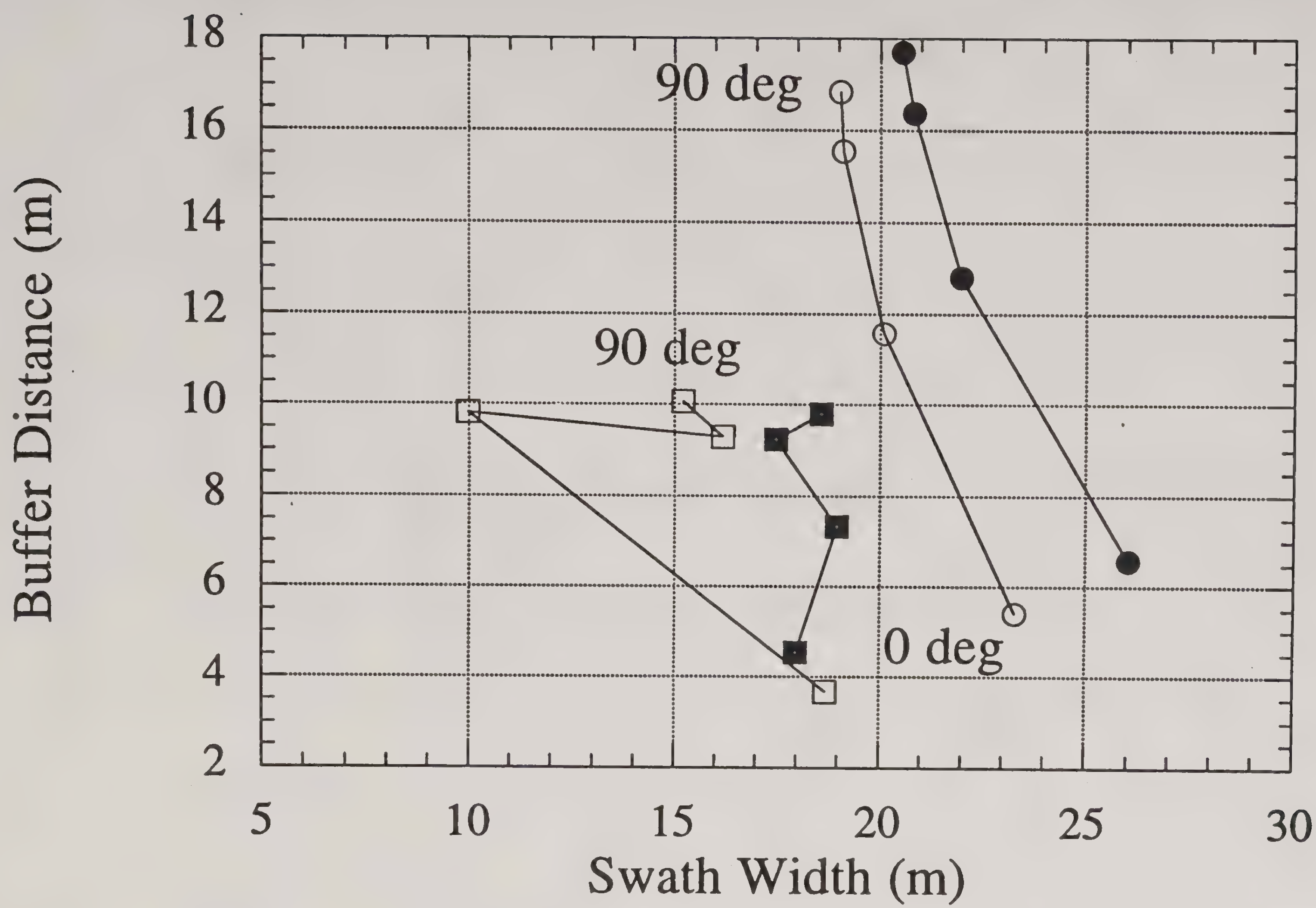

Figure 9c. Sensitivity of swath width and buffer distance to wind direction (0 to 90 deg relative to the aircraft flight line). The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

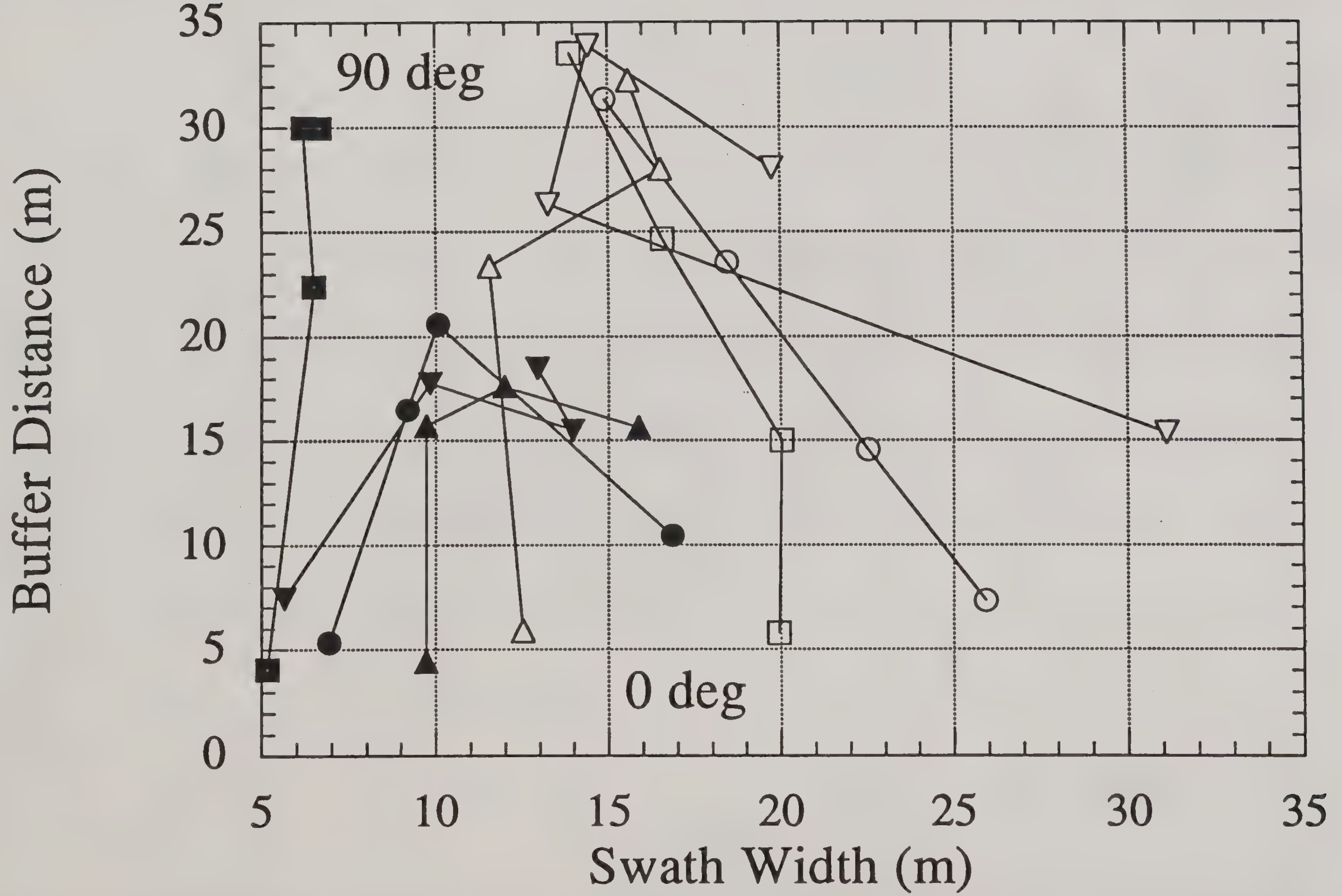

Figure 9d. Sensitivity of swath width and buffer distance to wind direction (0 to 90 deg relative to the aircraft flight line). The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

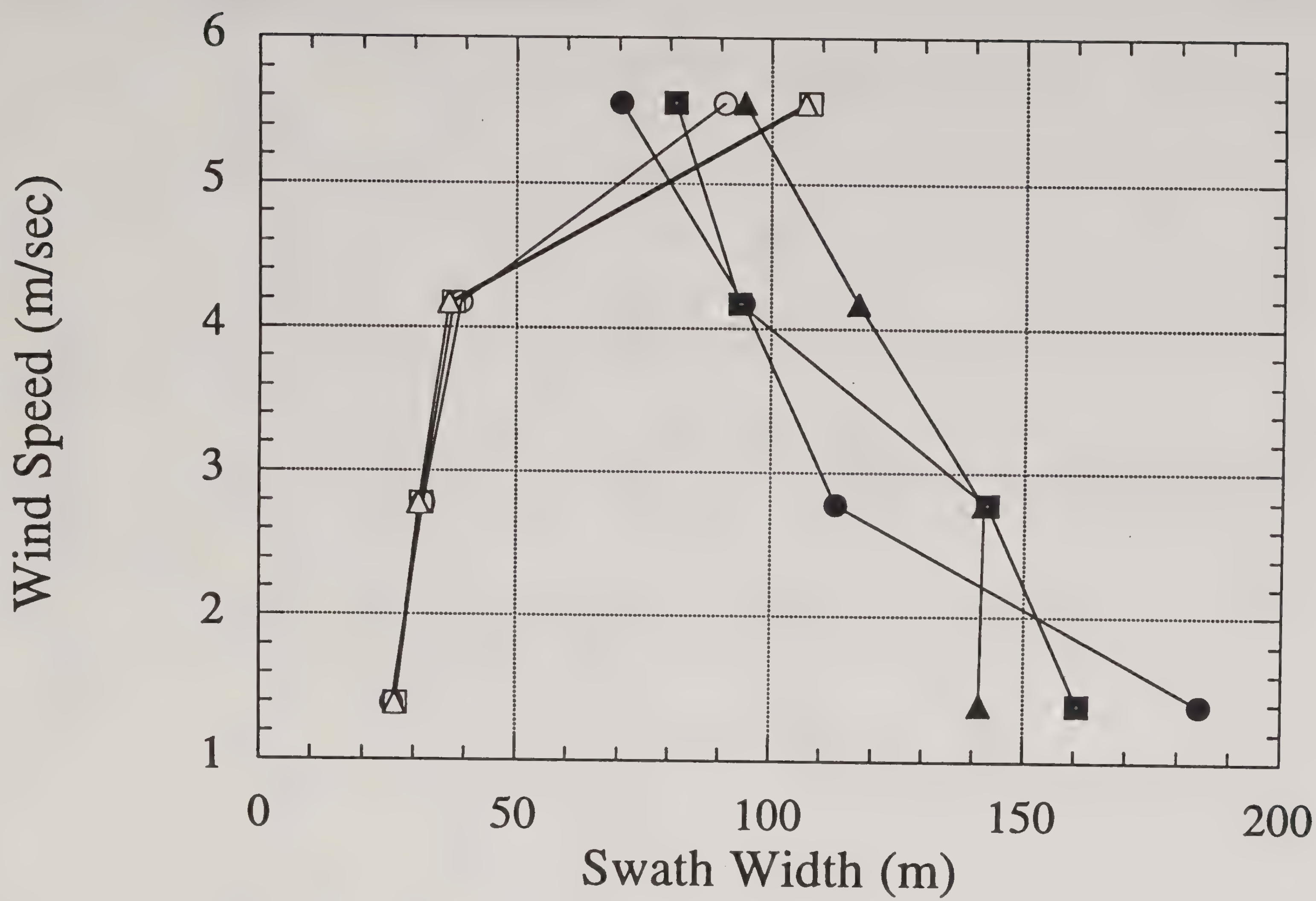

Figure 10a. Sensitivity of swath width to wind speed. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

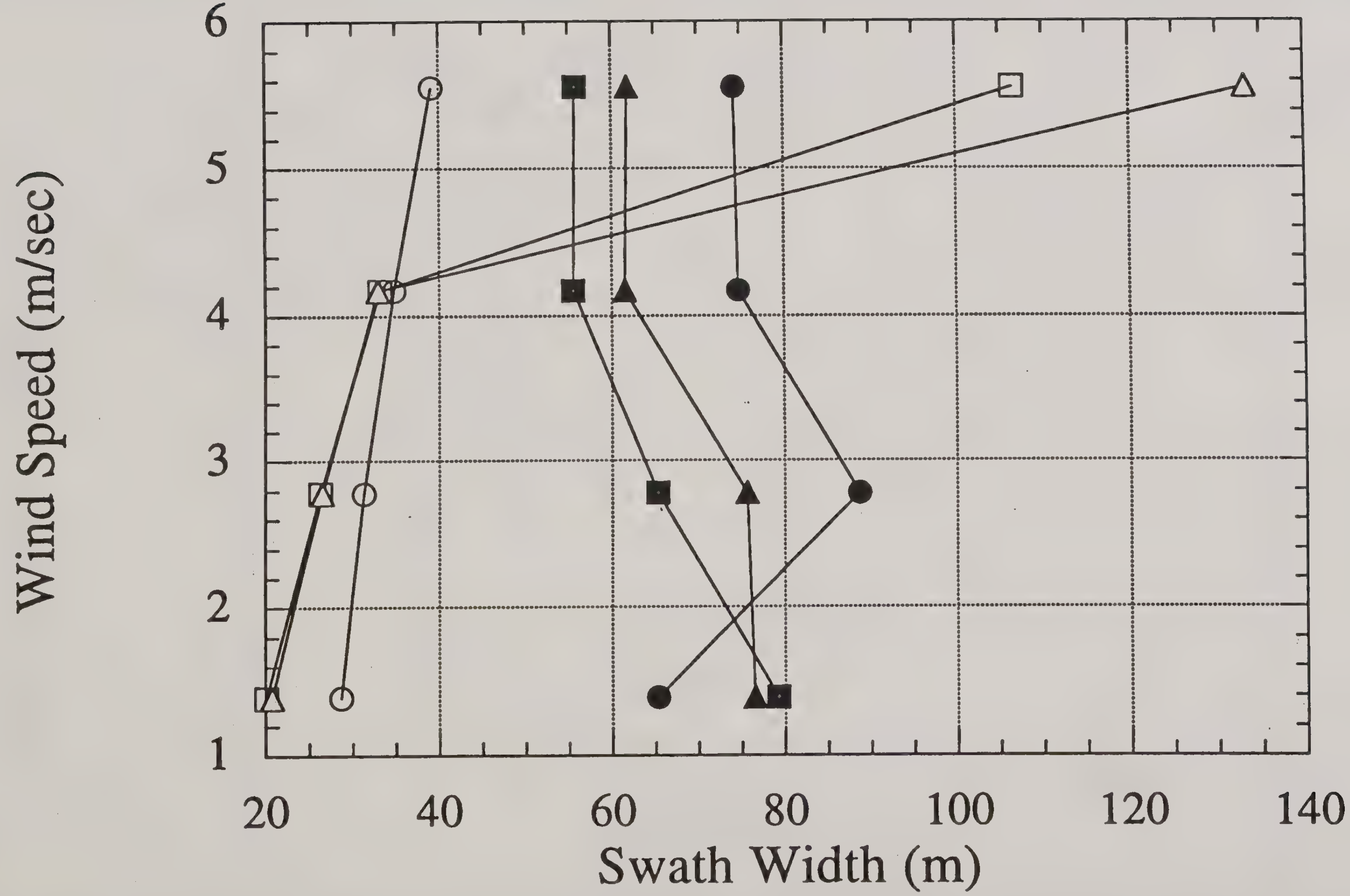

Figure 10b. Sensitivity of swath width to wind speed. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

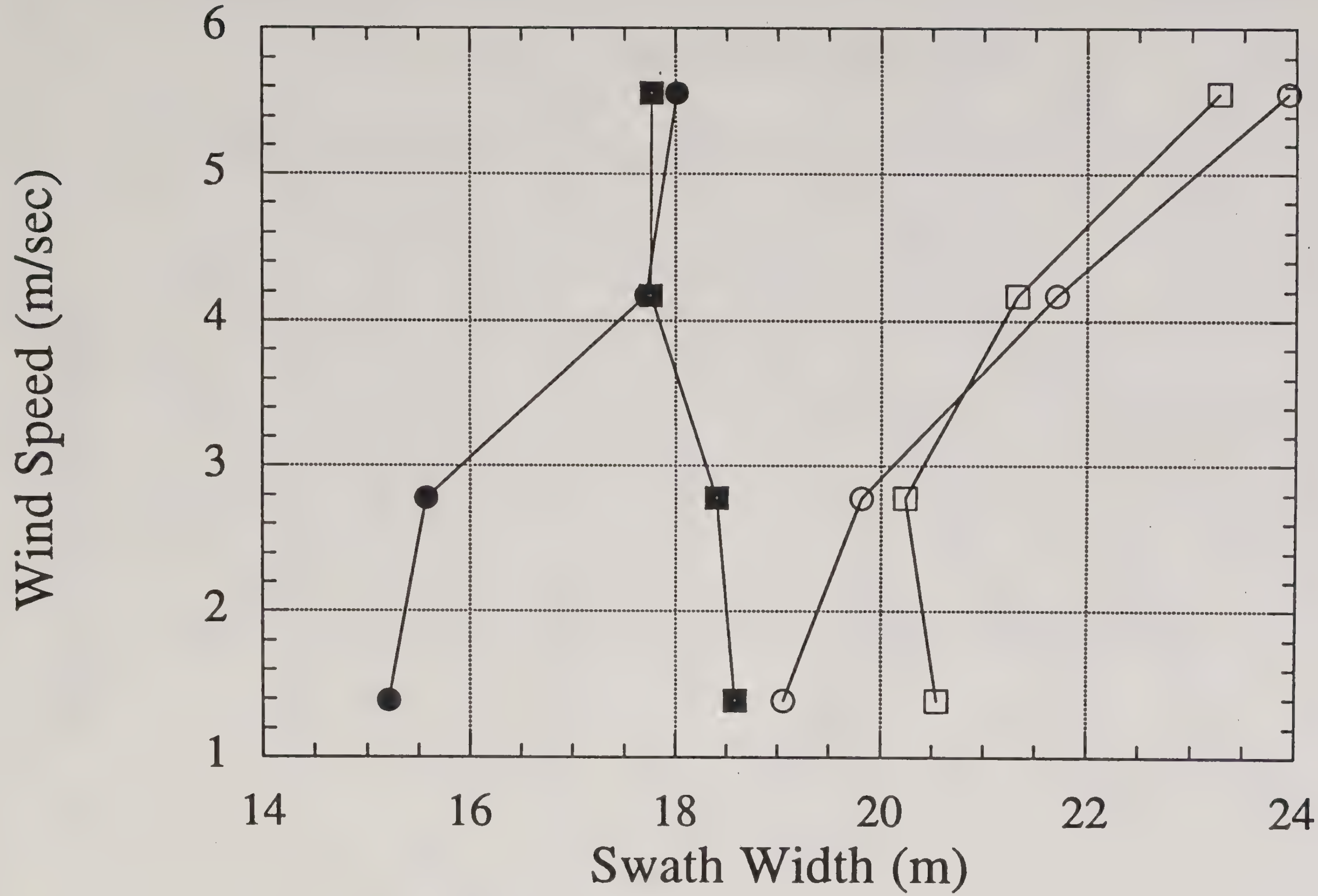

Figure 10c. Sensitivity of swath width to wind speed. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

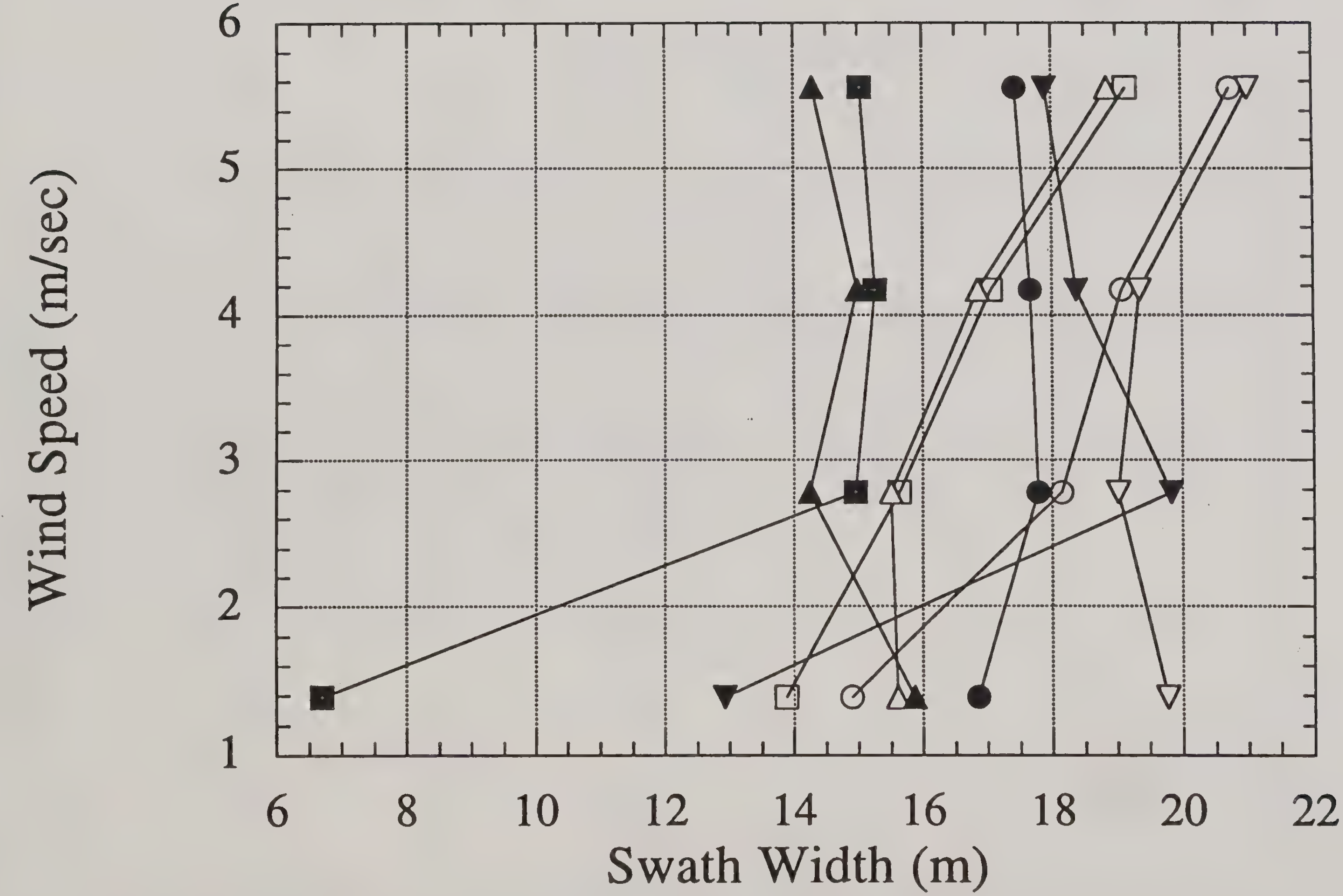

Figure 10d. Sensitivity of swath width to wind speed. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

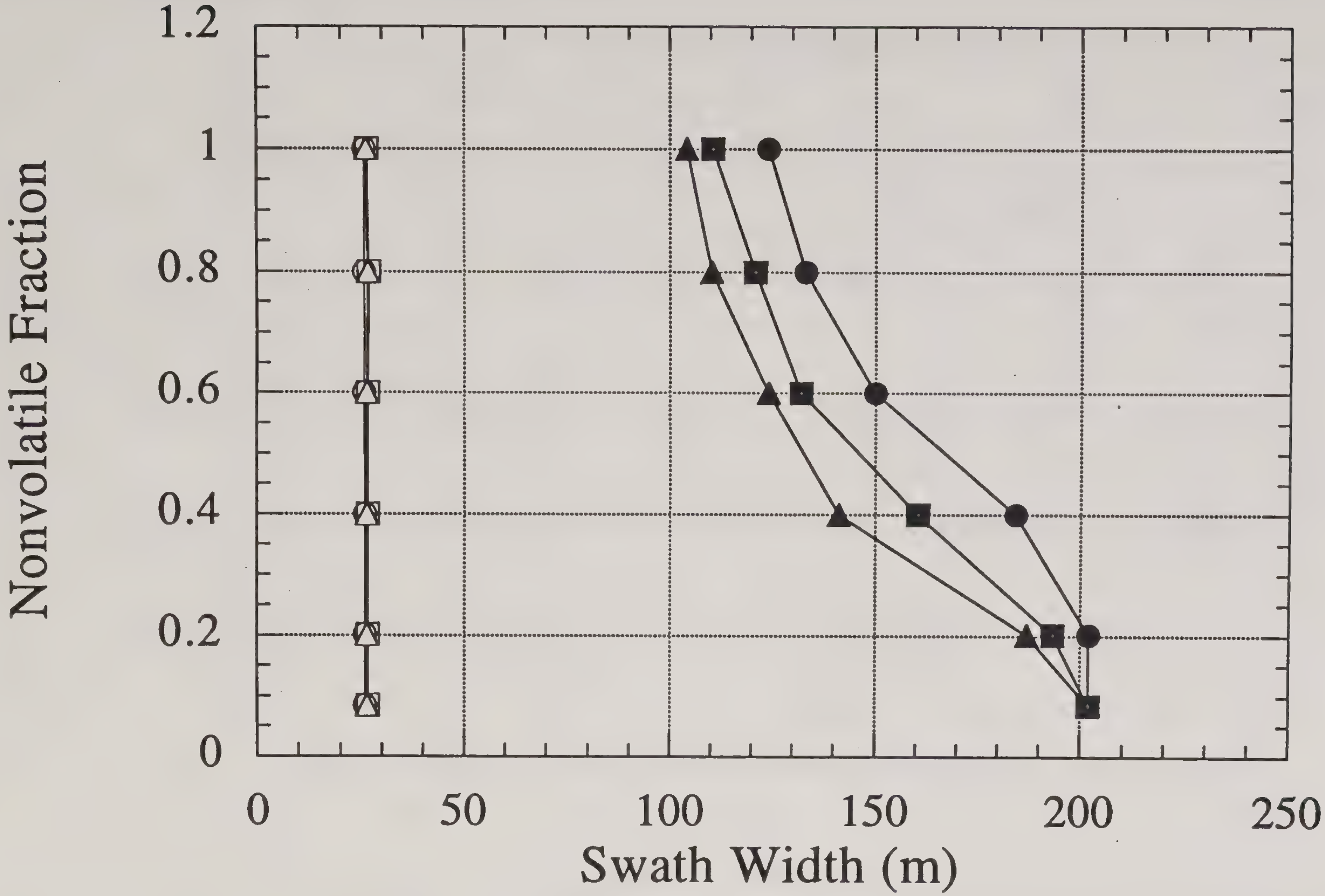

Figure 11a. Sensitivity of swath width to nonvolatile fraction. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

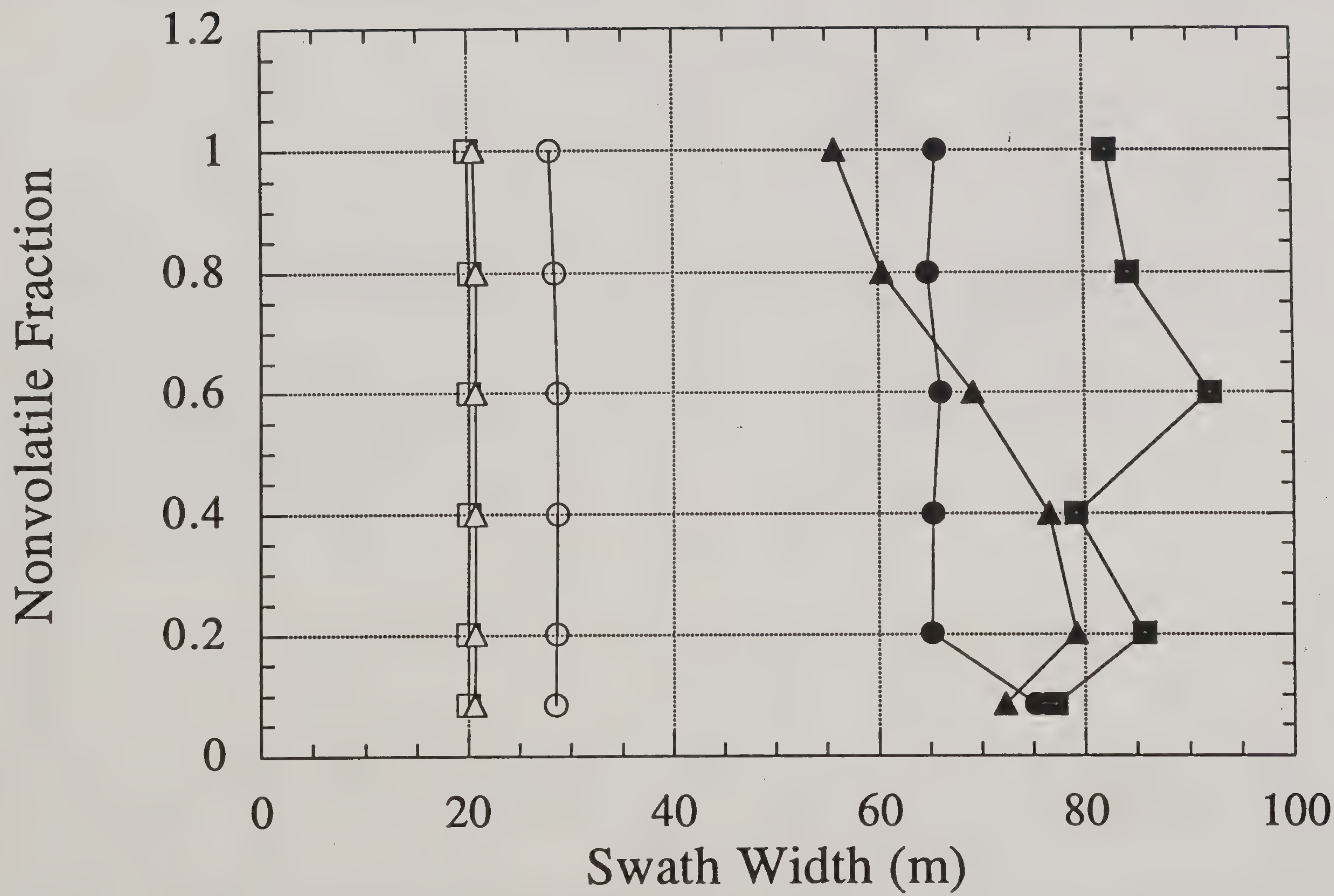

Figure 11b. Sensitivity of swath width to nonvolatile fraction. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

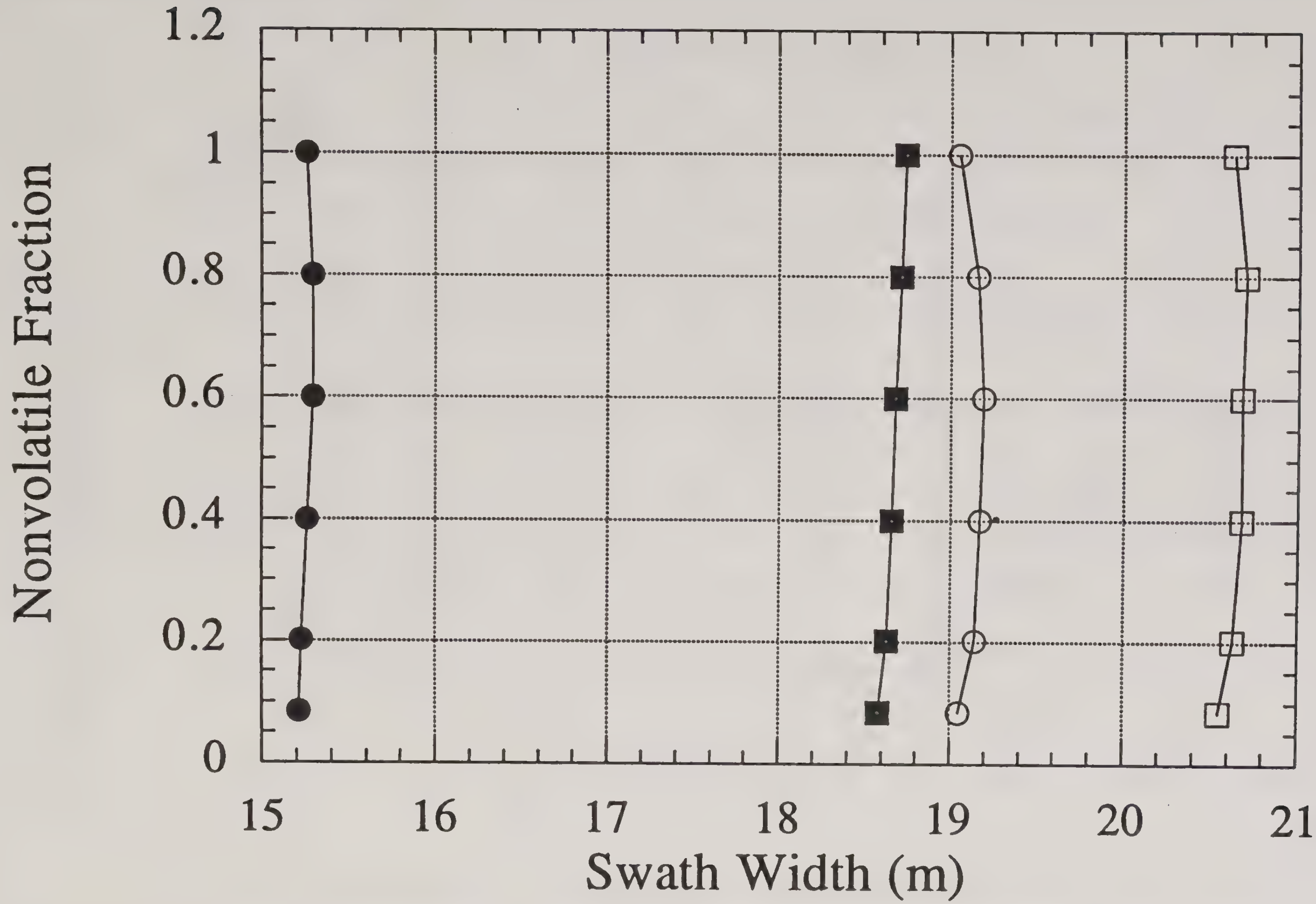

Figure 11c. Sensitivity of swath width to nonvolatile fraction. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

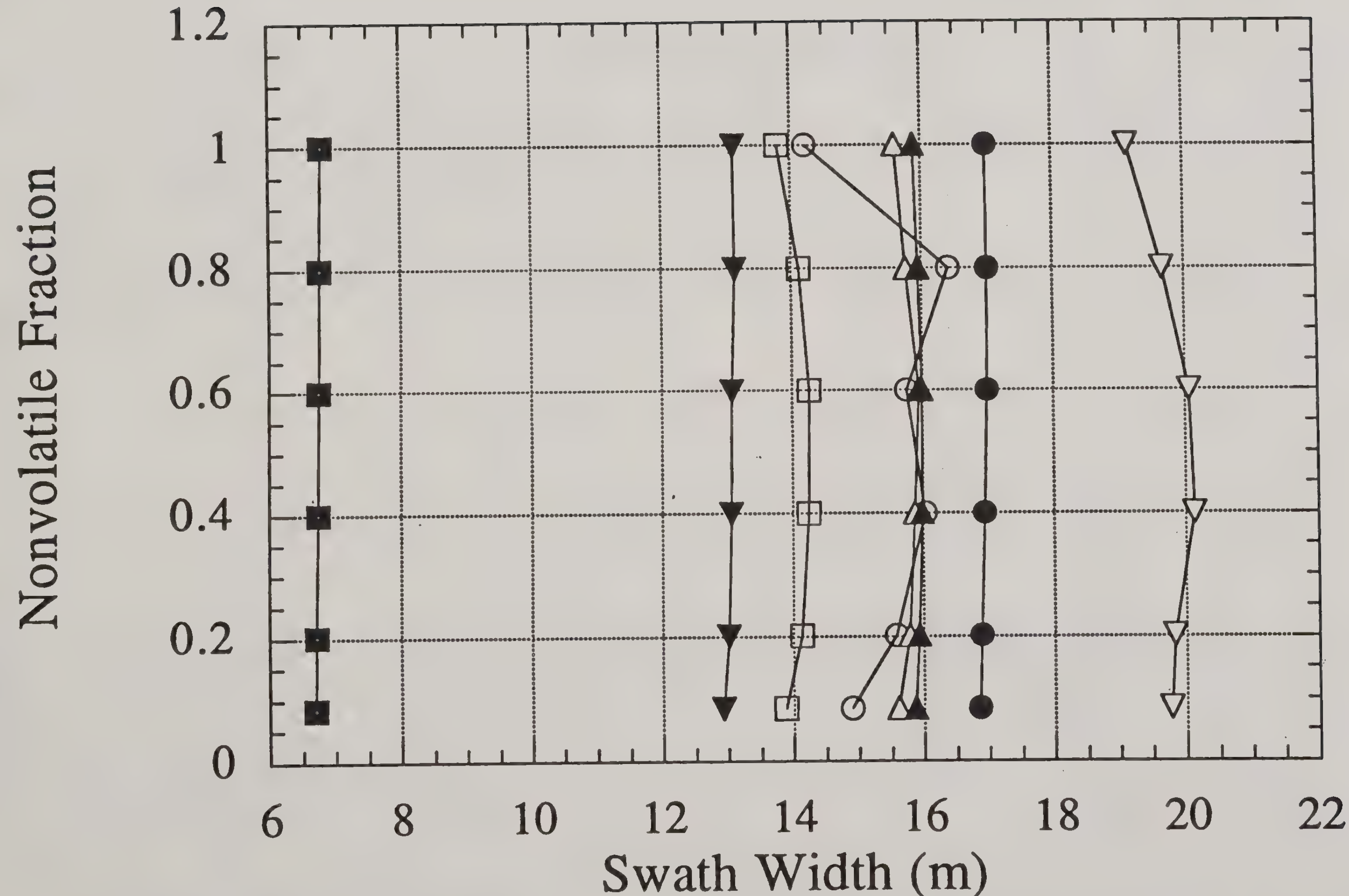

Figure 11d. Sensitivity of swath width to nonvolatile fraction. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

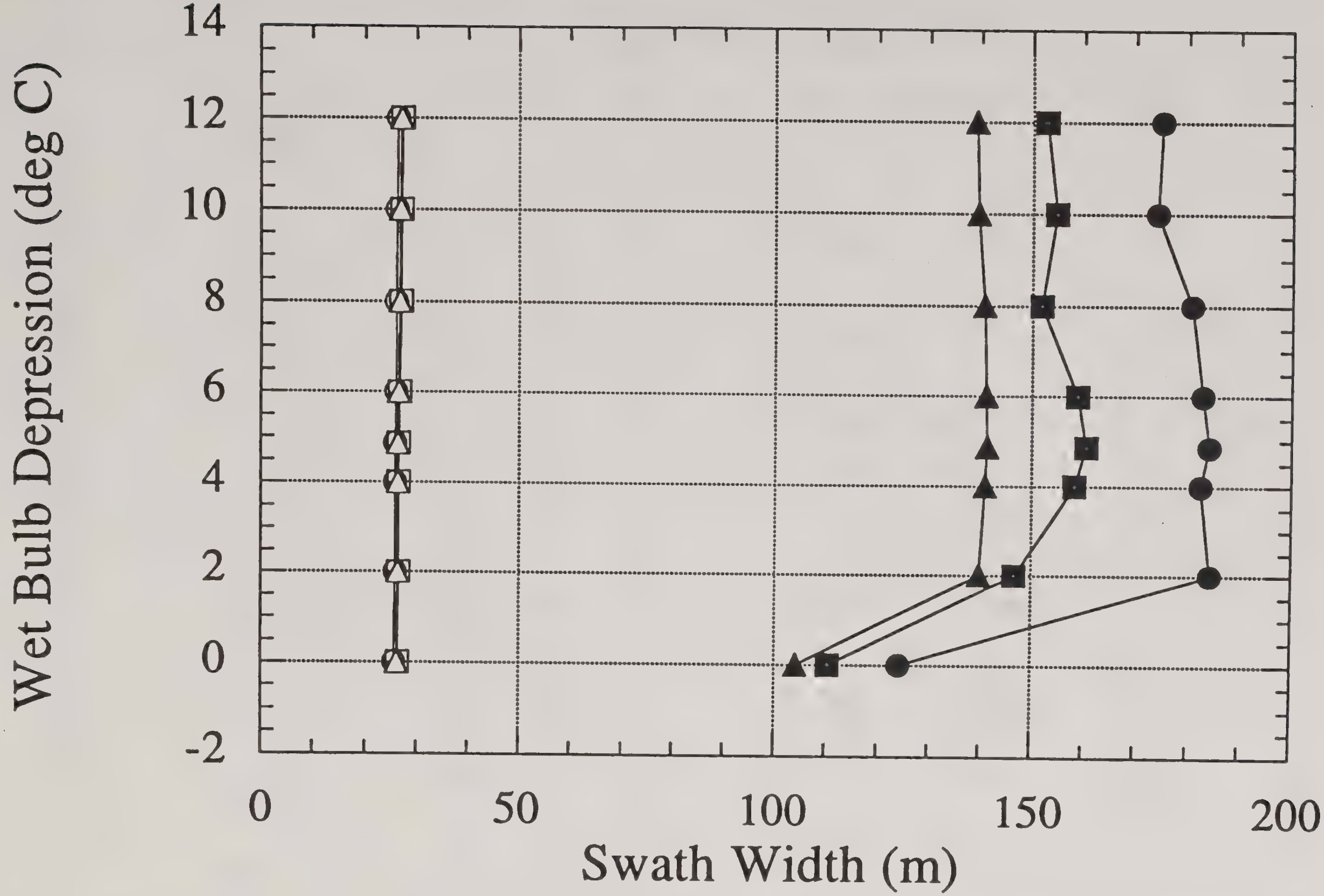

Figure 12a. Sensitivity of swath width to wet bulb temperature depression. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

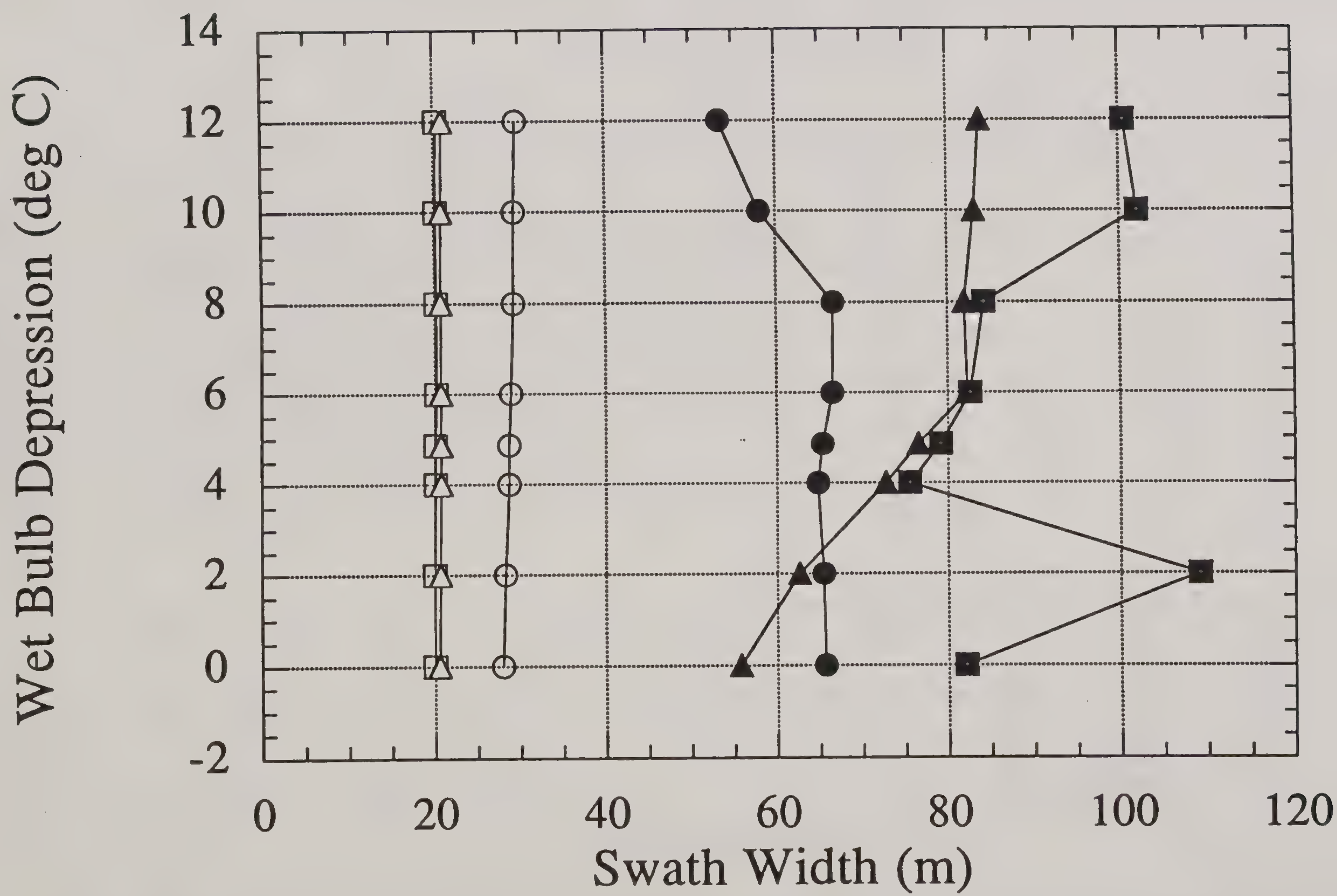

Figure 12b. Sensitivity of swath width to wet bulb temperature depression. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

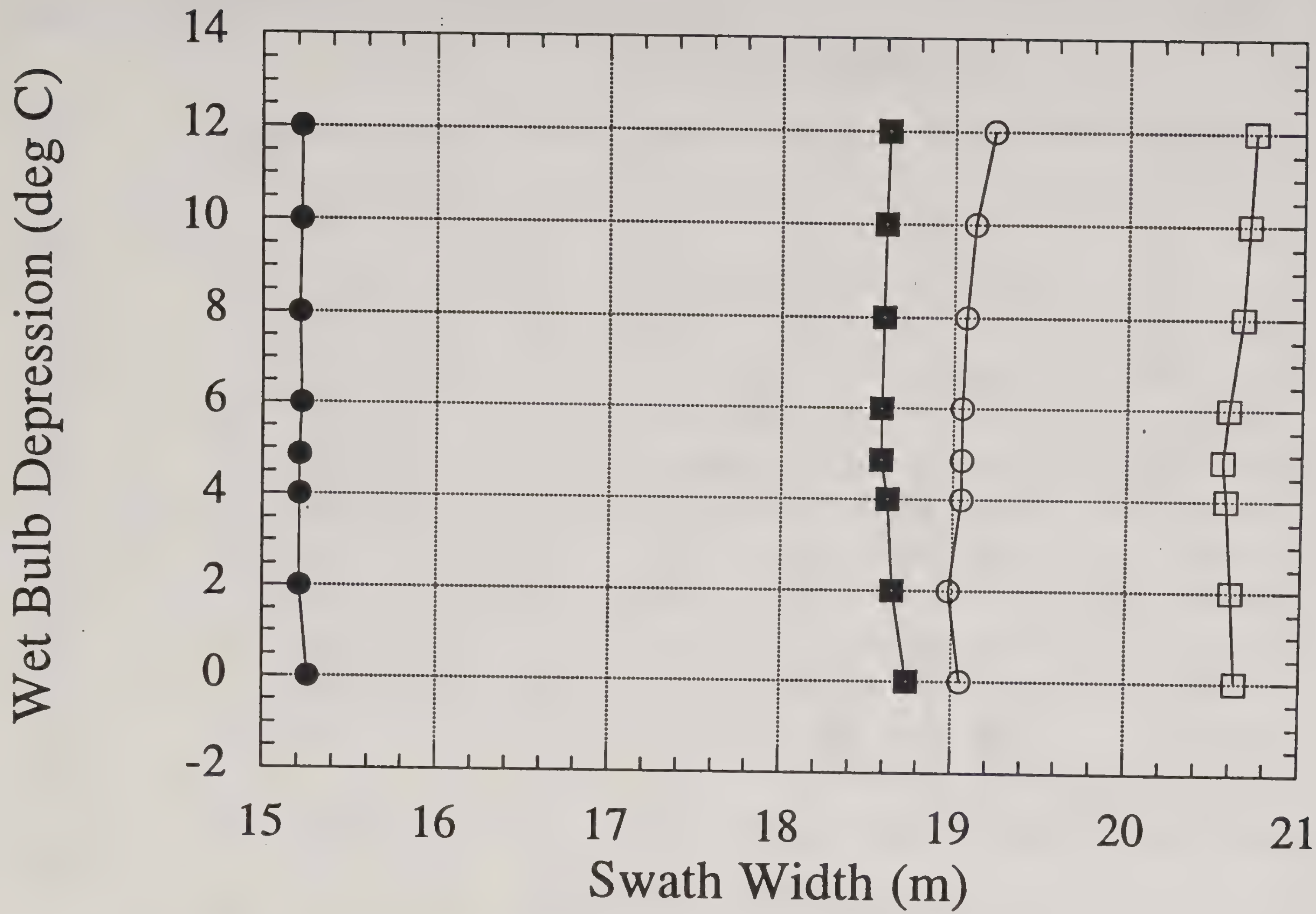

Figure 12c. Sensitivity of swath width to wet bulb temperature depression. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

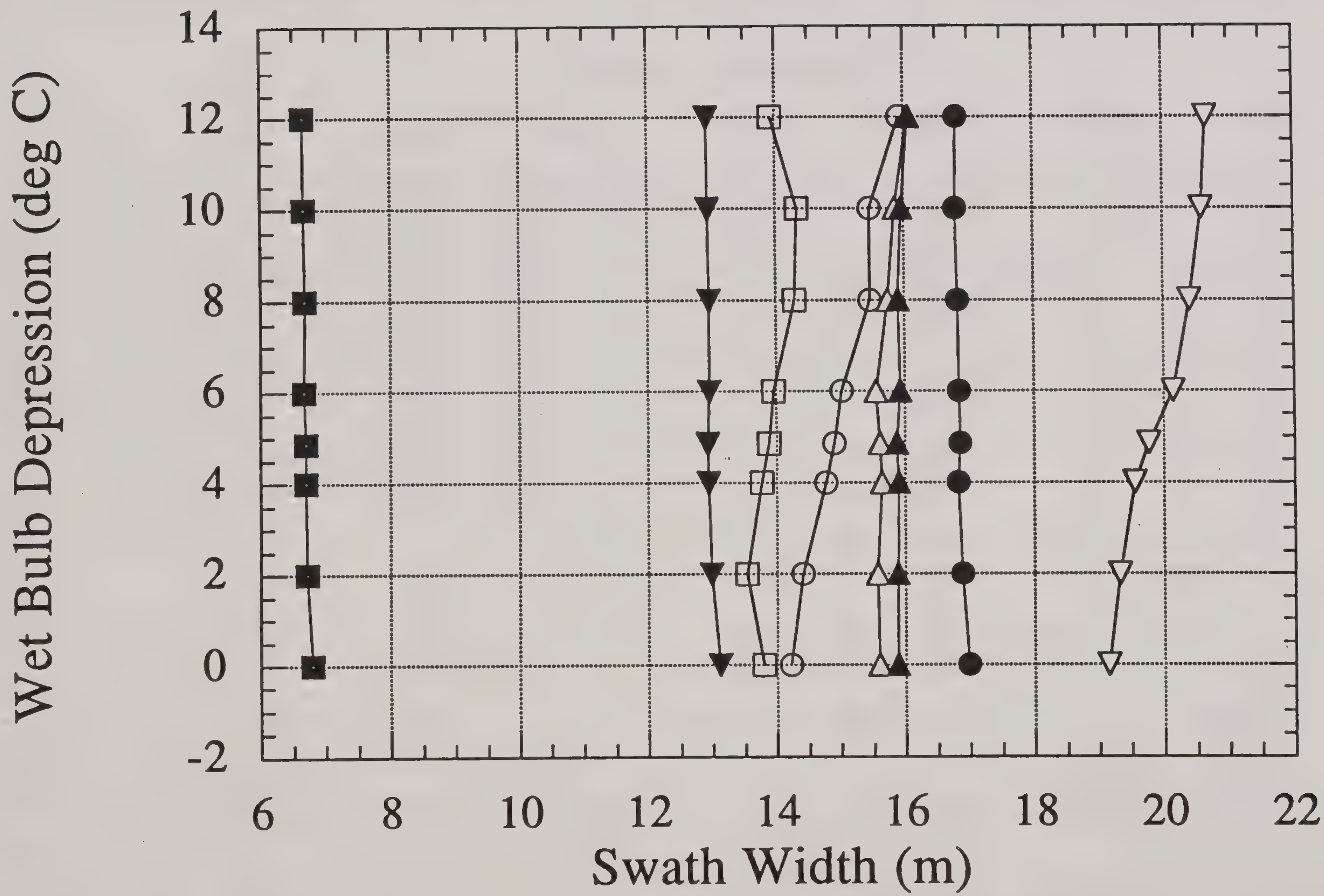

Figure 12d. Sensitivity of swath width to wet bulb temperature depression. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

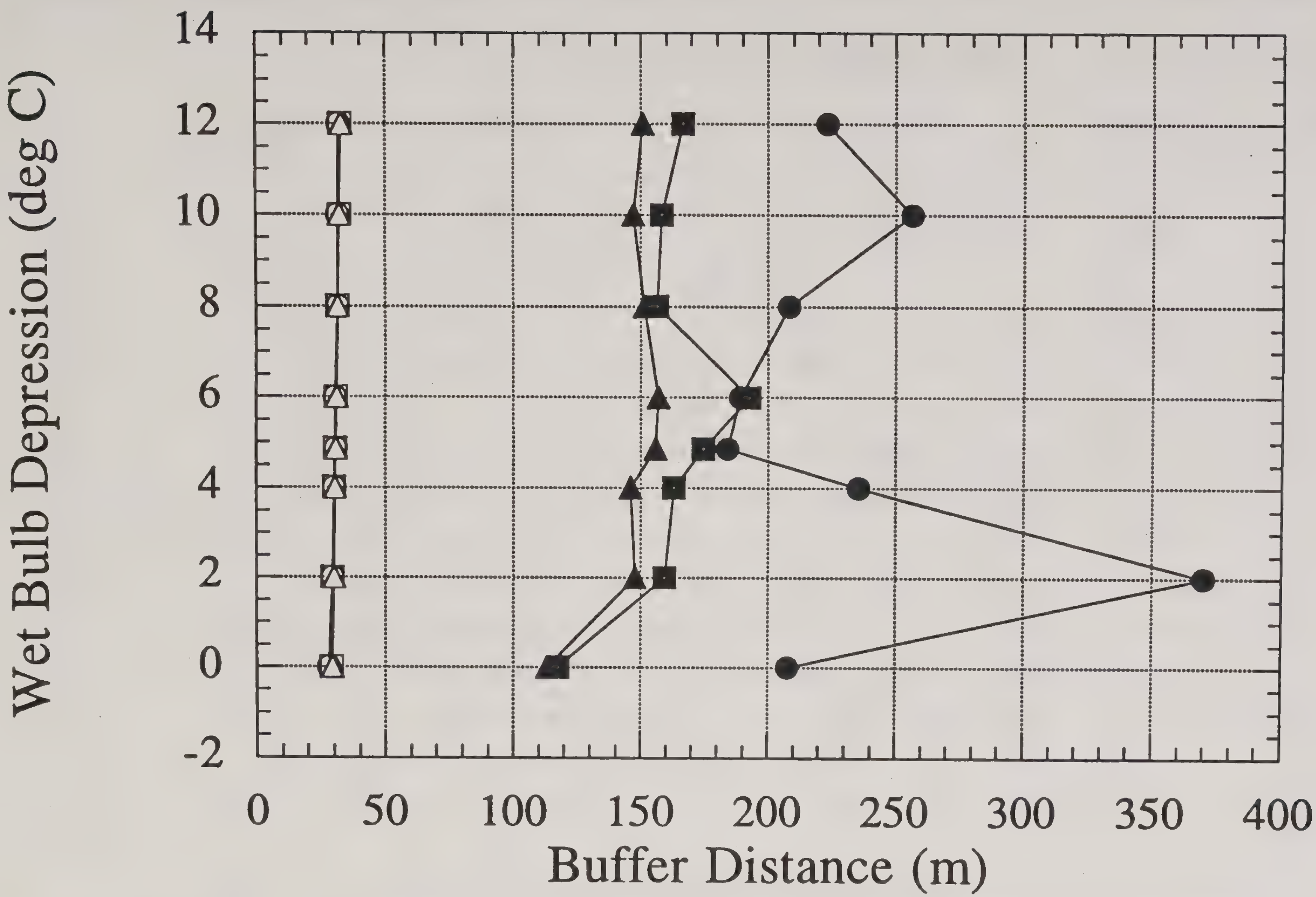

Figure 13a. Sensitivity of buffer distance to wet bulb temperature depression. The configurations represented are: Schweizer Ag Cat with D8/46 nozzles (○); Schweizer Ag Cat with Micronair rotary atomizers (●); Air Tractor AT-301 with D8/46 nozzles (□); Air Tractor AT-301 with Micronair rotary atomizers (■); Ayres Turbo Thrush with D8/46 nozzles (Δ); and Ayres Turbo Thrush with Micronair rotary atomizers (▲).

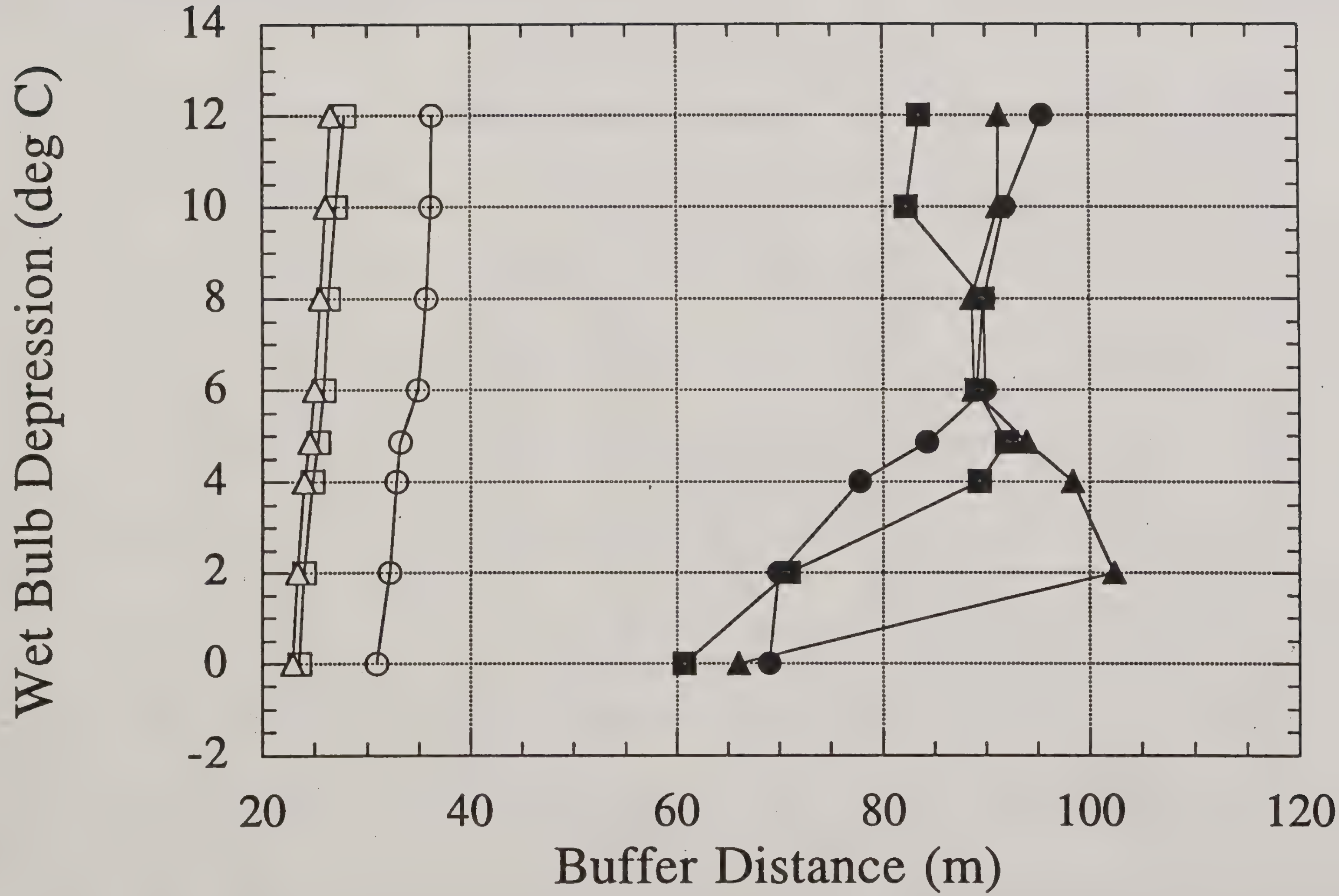

Figure 13b. Sensitivity of buffer distance to wet bulb temperature depression. The configurations represented are: Bell 205A with D8/46 nozzles (○); Bell 205A with Beecomist rotary atomizers (●); Bell JetRanger III with D8/46 nozzles (□); Bell JetRanger III with Beecomist rotary atomizers (■); Hiller Soloy Turbo with D8/46 nozzles (Δ); and Hiller Soloy Turbo with Beecomist rotary atomizers (▲).

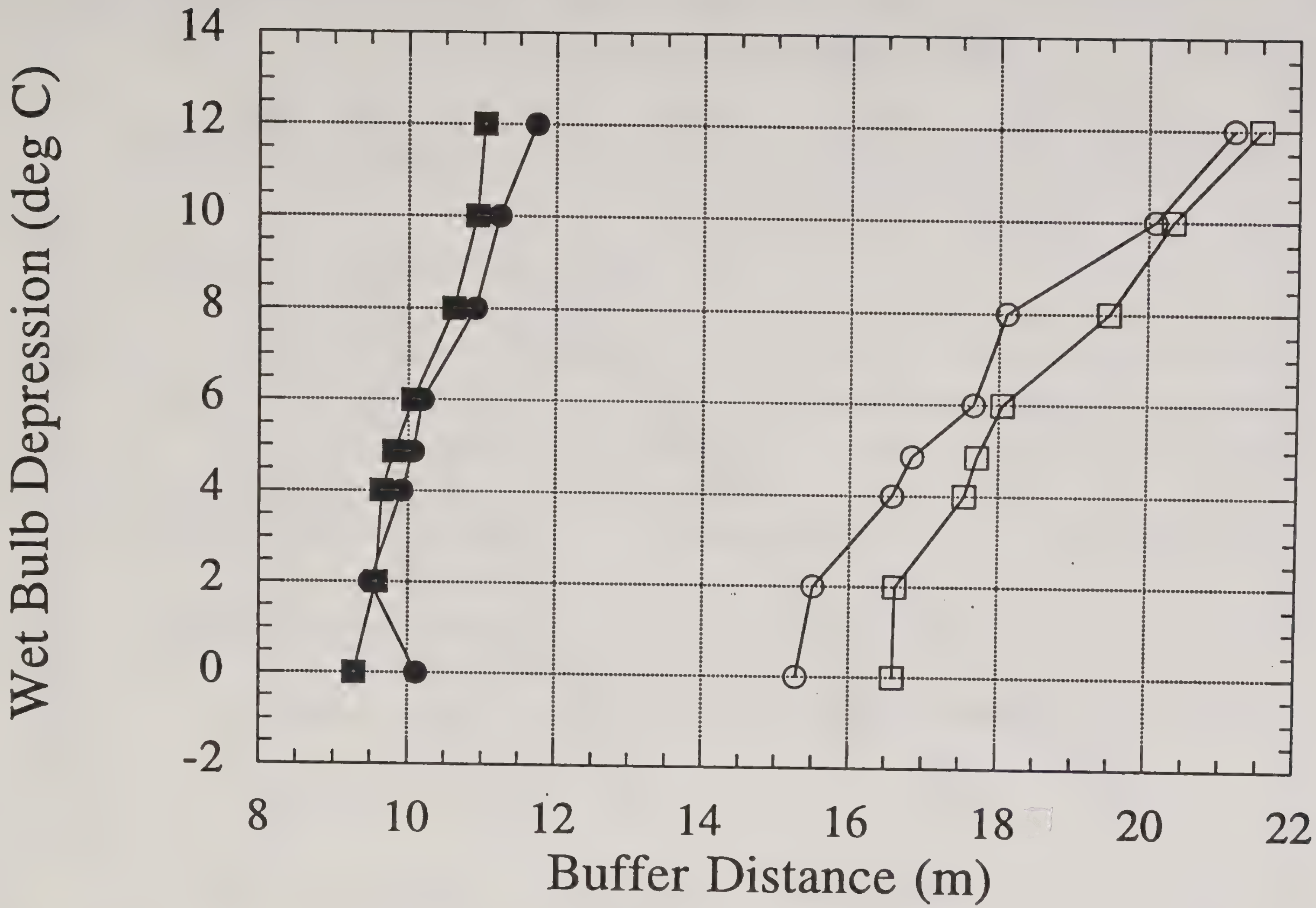

Figure 13c. Sensitivity of buffer distance to wet bulb temperature depression. The configurations represented are: Cessna Ag Wagon with D8/46 nozzles and smaller VMD (○); Cessna Ag Wagon with D8/46 nozzles and larger VMD (●); Fletcher with D8/46 nozzles and smaller VMD (□); and Fletcher with D8/46 nozzles and larger VMD (■).

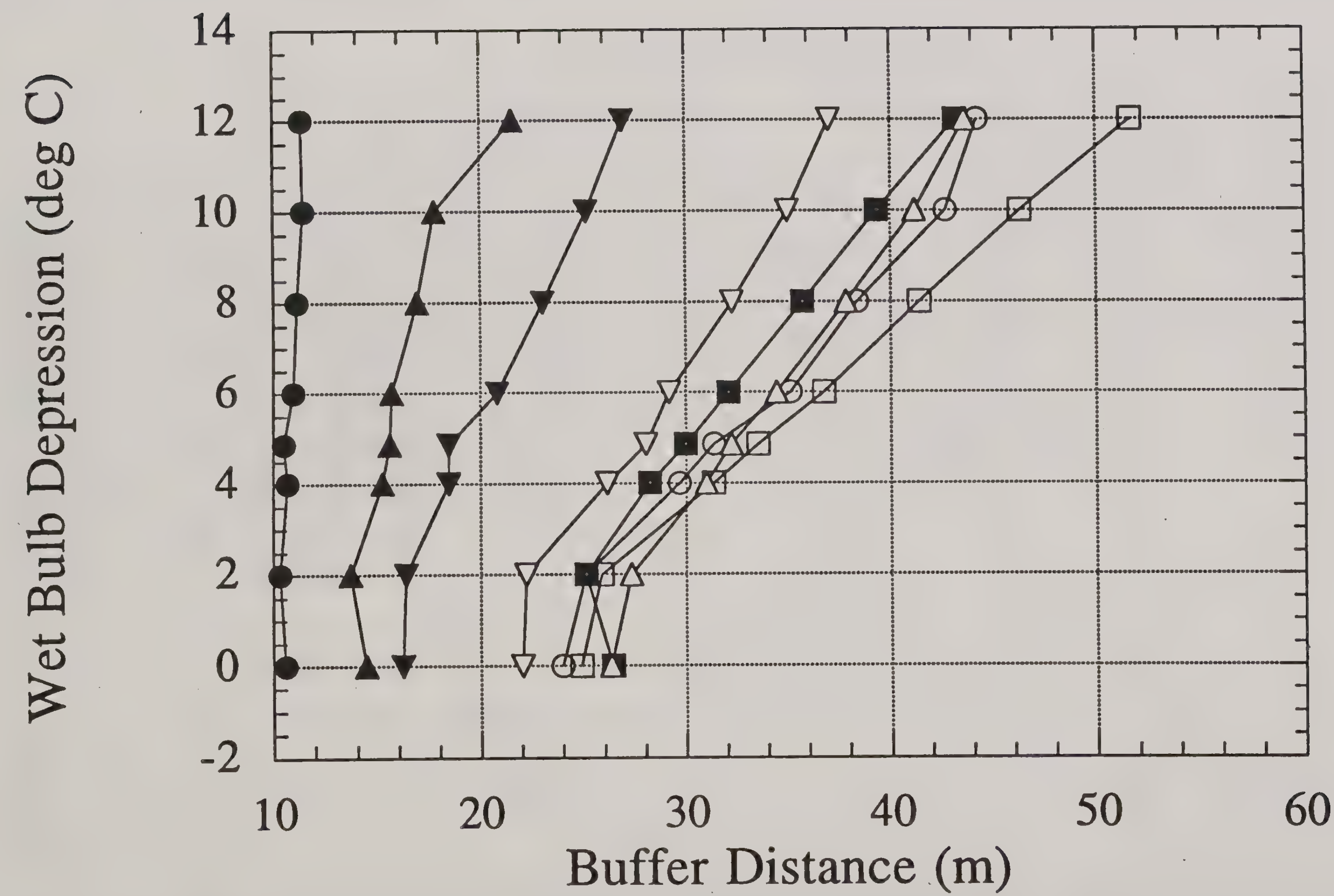

Figure 13d. Sensitivity of buffer distance to wet bulb temperature depression. The configurations represented are: Bell JetRanger III with D8/46 nozzles and smaller VMD (○); Bell JetRanger III with D8/46 nozzles and larger VMD (●); Hughes 300C with D8/46 nozzles and smaller VMD (□); Hughes 300C with D8/46 nozzles and larger VMD (■); Hughes Cayuse 500C with D8/46 nozzles and smaller VMD (Δ); Hughes Cayuse 500C with D8/46 nozzles and larger VMD (▲); Squirrel with D8/46 nozzles and smaller VMD (∇); and Squirrel with D8/46 nozzles and larger VMD (▼).

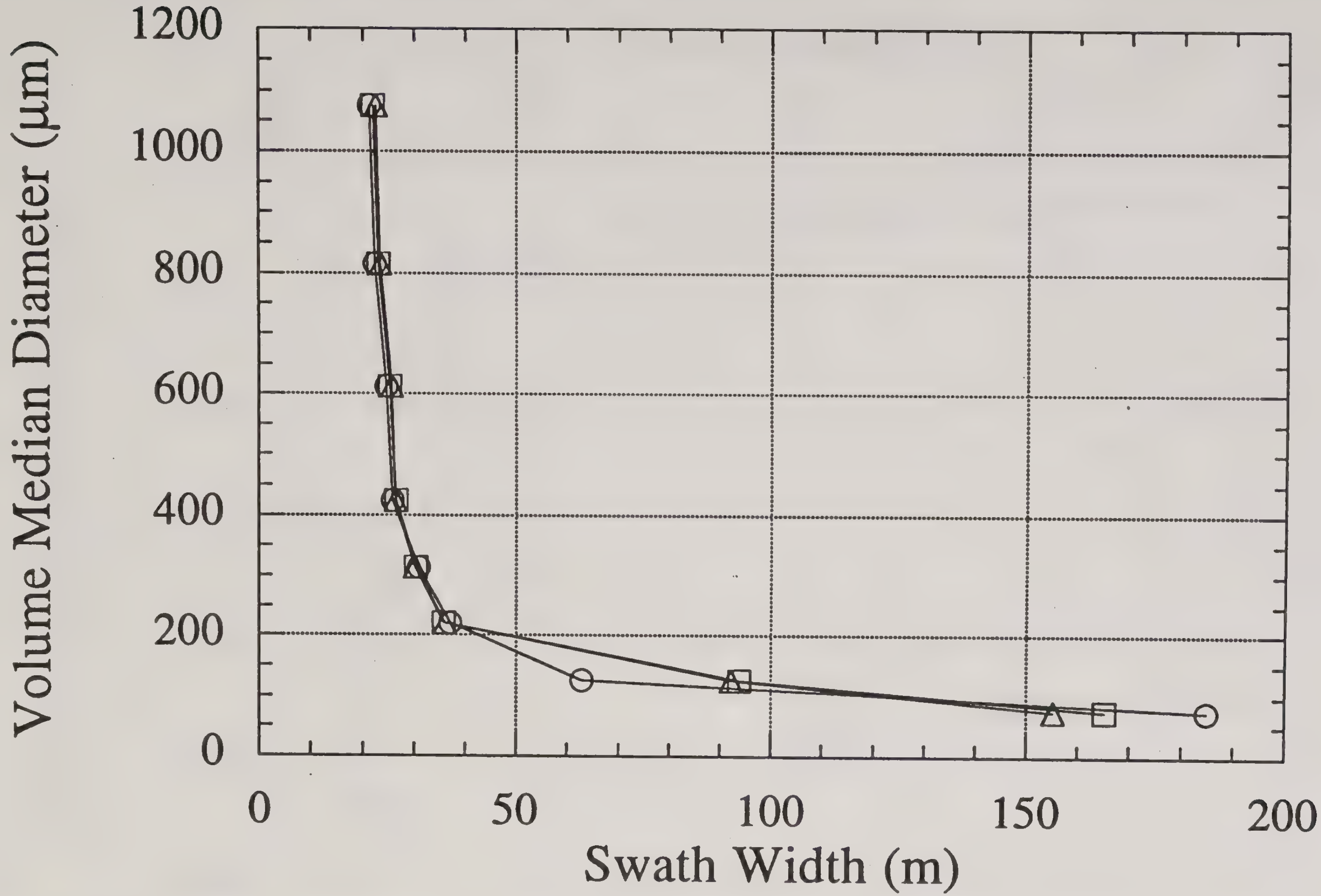

Figure 14a. Sensitivity of swath width to volume median diameter. The configurations represented are: Schweizer Ag Cat (○); Air Tractor AT-301 (□); and Ayres Turbo Thrush (Δ).

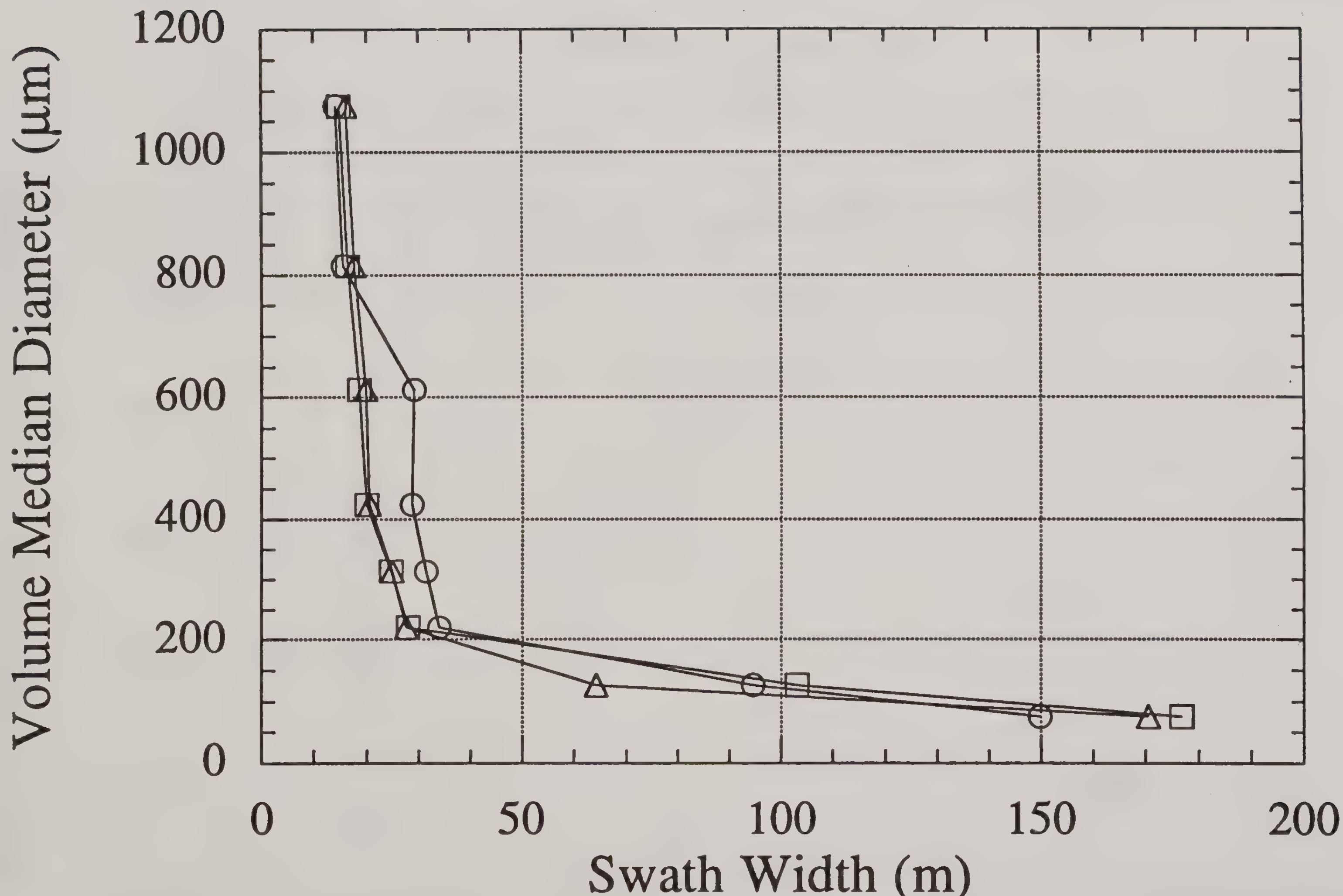

Figure 14b. Sensitivity of swath width to volume median diameter. The configurations represented are: Bell 205A (○); Bell JetRanger III (□); and Hiller Soloy Turbo (Δ).

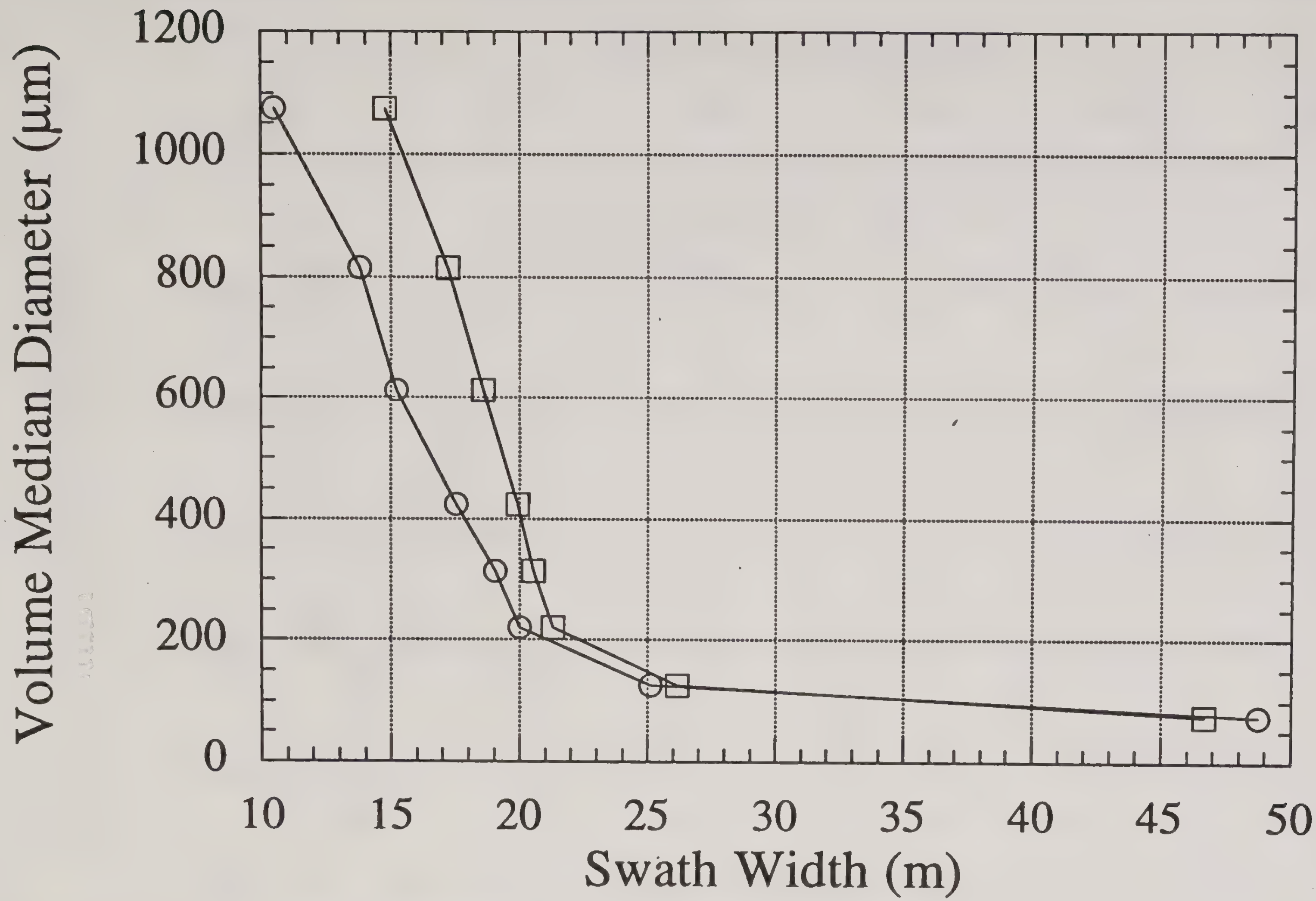

Figure 14c. Sensitivity of swath width to volume median diameter. The configurations represented are: Cessna Ag Wagon (○) and Fletcher (□).

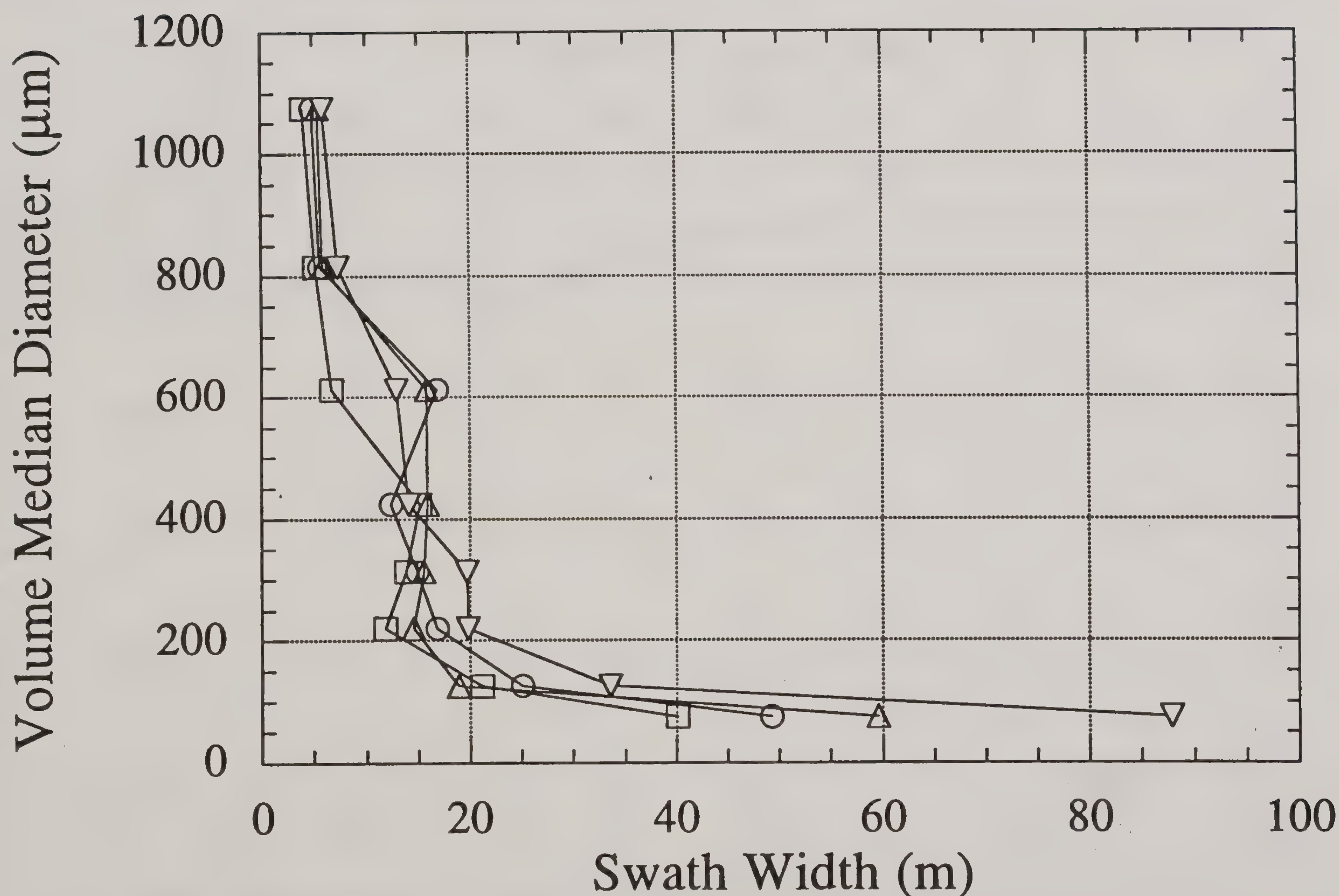

Figure 14d. Sensitivity of swath width to volume median diameter. The configurations represented are: Bell JetRanger III (○); Hughes 300C (□); Hughes Cayuse 500C (Δ); and Squirrel (∇).

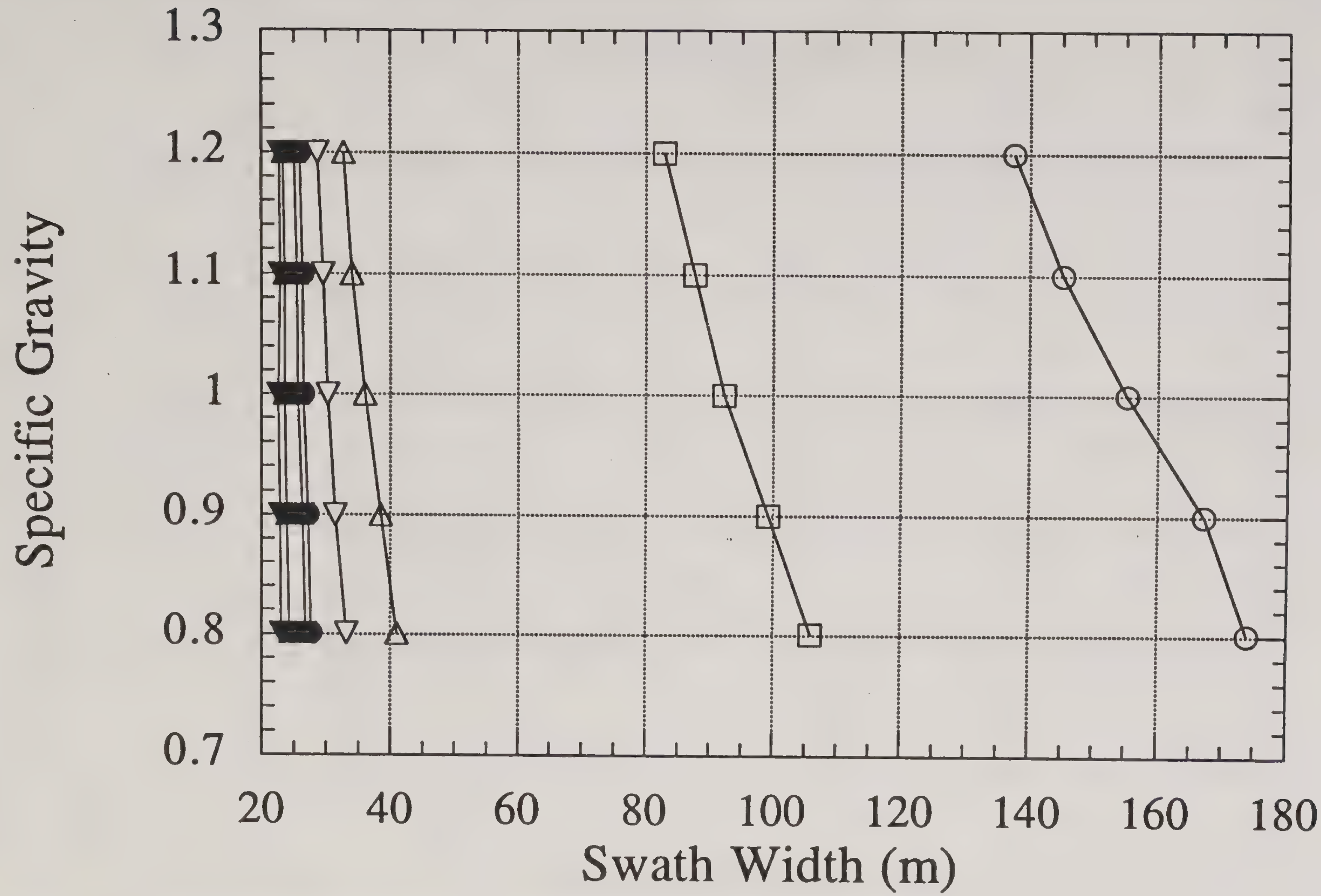

Figure 15a. Sensitivity of swath width to specific gravity for the Ayres Turbo Thrush. The configurations represented are for VMDs of: 74.5 μm (○); 125.1 μm (□); 220.8 μm (Δ); 314.0 μm (∇); 423.9 μm (●); 613.0 μm (■); 815.5 μm (▲); and 1075.5 μm (▼).

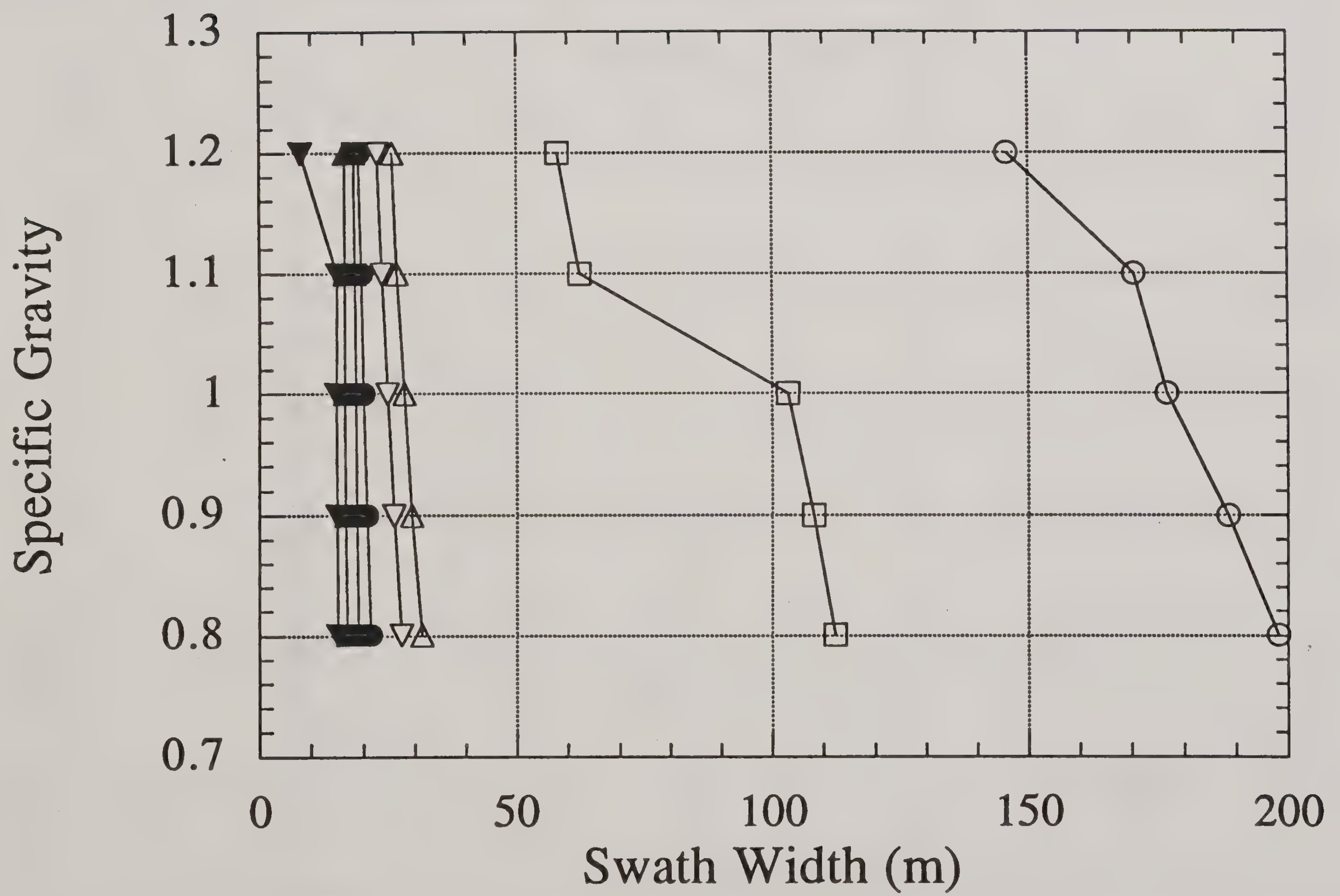

Figure 15b. Sensitivity of swath width to specific gravity for the Bell JetRanger III (US configuration). The configurations represented are for VMDs of: 74.5 µm (○); 125.1 µm (□); 220.8 µm (Δ); 314.0 mm (∇); 423.9 µm (●); 613.0 µm (■); 815.5 µm (▲); and 1075.5 µm (▼).

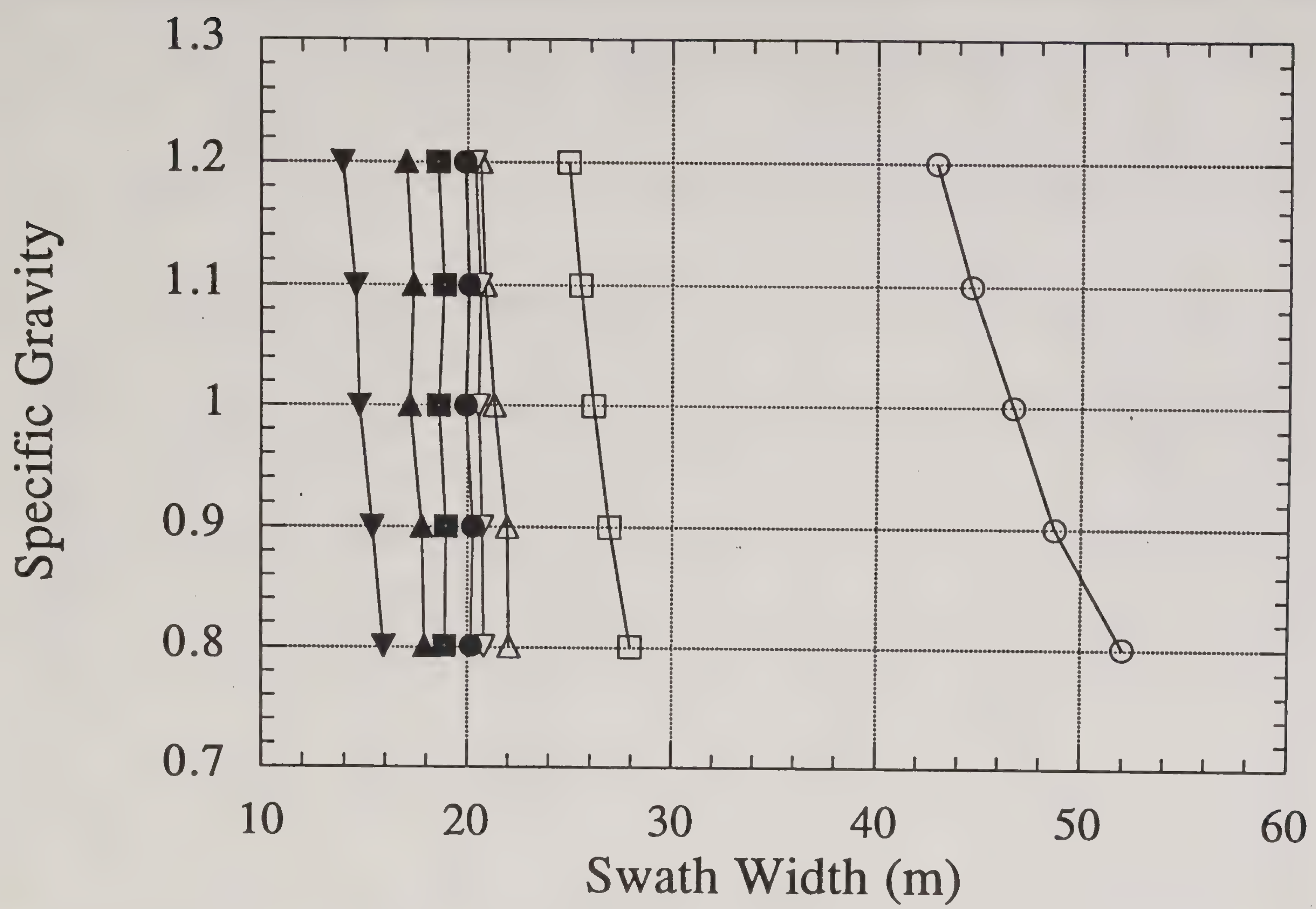

Figure 15c. Sensitivity of swath width to specific gravity for the Fletcher. The configurations represented are for VMDs of: 74.5 µm (○); 125.1 µm (□); 220.8 µm (Δ); 314.0 µm (∇); 423.9 µm (●); 613.0 µm (■); 815.5 µm (▲); and 1075.5 µm (▼).

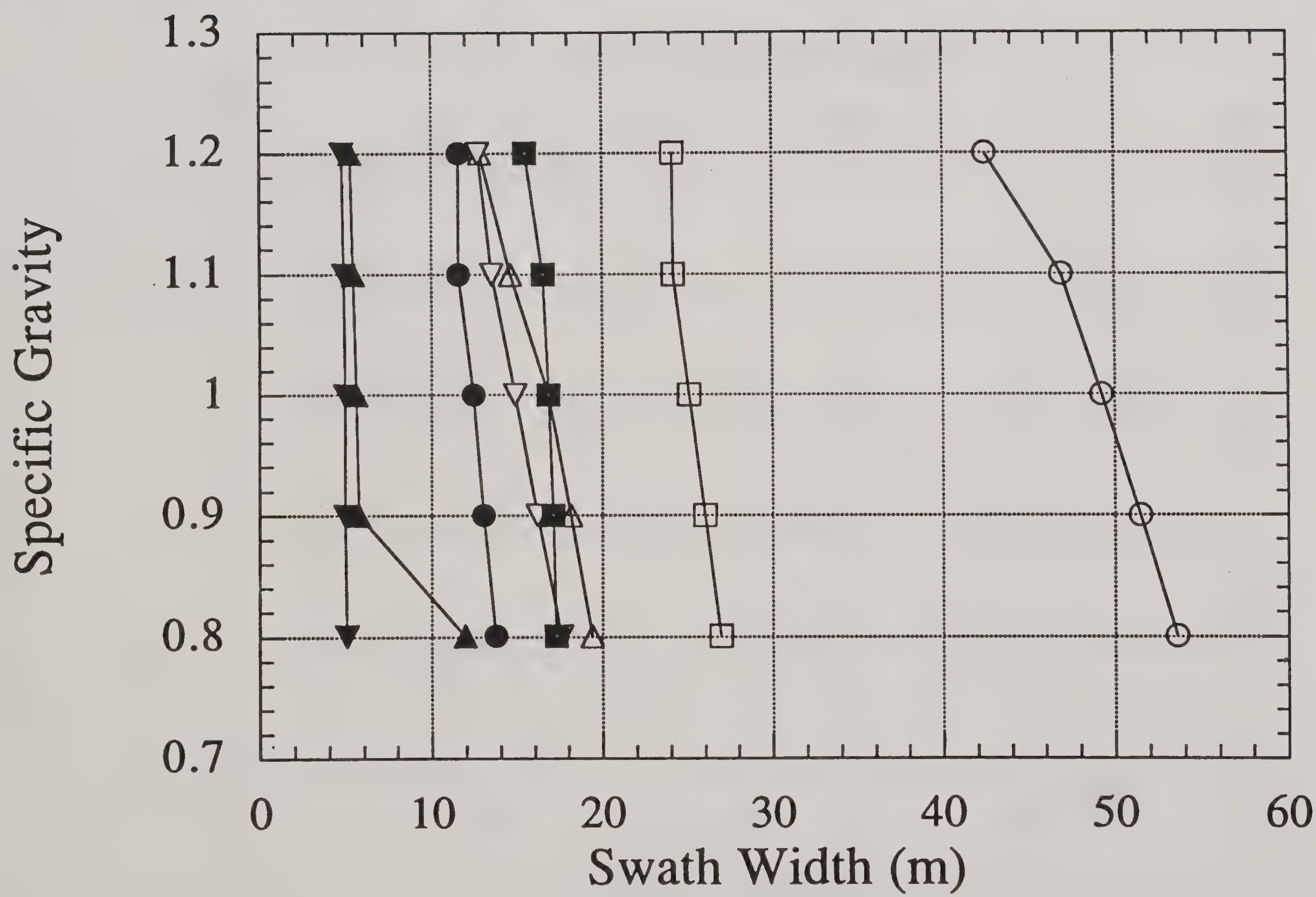

Figure 15d. Sensitivity of swath width to specific gravity for the Bell JetRanger III (NZ configuration). The configurations represented are for VMDs of: 74.5 µm (○); 125.1 µm (□); 220.8 µm (Δ); 314.0 µm (∇); 423.9 µm (●); 613.0 µm (■); 815.5 µm (▲); and 1075.5 µm (▼).

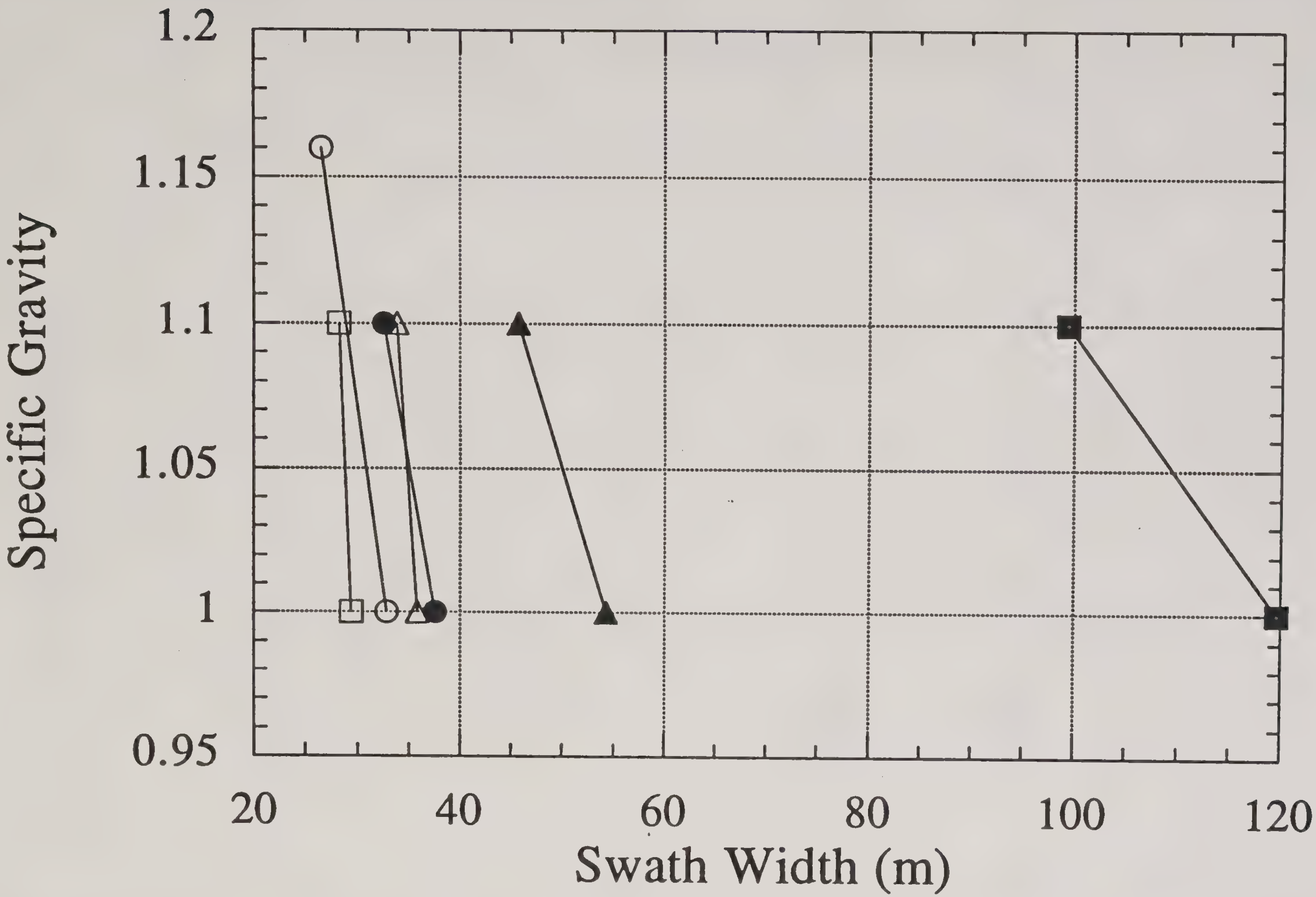

Figure 16a. Sensitivity of swath width to specific gravity for the Ayres Turbo Thrush. The configurations represented are those found on page 10: 8004 nozzles spraying Foray 48B (○); 8006 nozzles spraying Gypcheck (□); 8010 nozzles spraying TM-Biocontrol (Δ); 8010 nozzles spraying Gypcheck (●); Micronair rotary atomizers spraying TM-Biocontrol (■); and Micronair rotary atomizers spraying Gypcheck (▲).

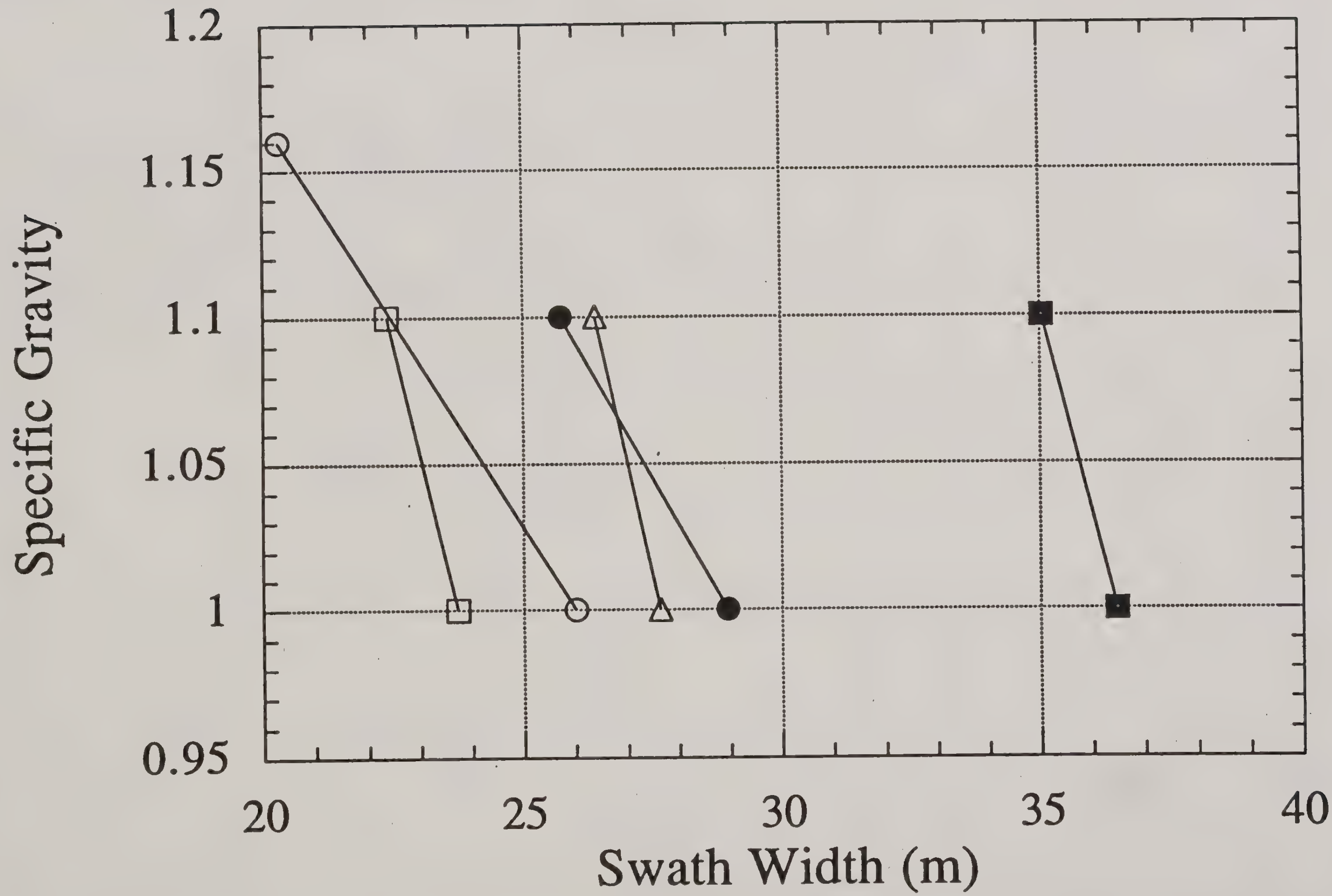

Figure 16b. Sensitivity of swath width to specific gravity for the Bell JetRanger III (US configuration). The configurations represented are those found on page 10: 8004 nozzles spraying Foray 48B (○); 8006 nozzles spraying Gypcheck (□); 8010 nozzles spraying TM-Biocontrol (Δ); 8010 nozzles spraying Gypcheck (●); and Beecomist rotary atomizers spraying TM-Biocontrol (■).

5. Database Application

With the database developed from the sensitivity study, we can move forward into developing a numerical algorithm that will recover data trends from any well-defined aerial application problem. What is anticipated here is the development of an influence coefficient approach, developing rates of change for all tested variables as a function of the changed input, for the five parameters described in Section 4 (maximum single swath deposition, swath width, average in-swath deposition, standard deviation of in-swath deposition, and buffer distance). The Training Module of SpraySafe Manager, and the Near-Wake Sensitivity Library in FSCBG, will then access these data to make quick estimates of the effect of input parameter changes. In this way the model will provide a fast way of responding to the user who is wondering what would happen if the value of one (or several) input variables changed, without running the model.

The actual approach will be developed and reported in a follow-on USDA Forest Service sponsored task.

6. Summary of Results

The extensive near-wake sensitivity study generated the following summary of swath width sensitivity to model input changes:

Boom Width

Swath width generally increases as boom width increases, but with some considerable variation for the rotary atomizers. The NZ configuration has apparently too low a release height to give any effective trends here.

Release (Boom) Height

Swath width is strongly affected by release height, generally increasing rapidly with increasing release height. For the rotary atomizers a maximum swath width is predicted, after which further increase in release height decreases the swath width (but increases downwind drift).

Spraying Speed

Swath width is affected slightly by spraying speed for the D8/46 nozzles, but is dramatically increased with increasing spraying speed for the rotary atomizers. The effect of spraying speed on swath width for the smaller drop sizes is an important finding of this study.

Aircraft Weight

Swath width is affected slightly by aircraft weight for the larger drop sizes, but significantly affected for the smaller drop sizes. There are important differences in aircraft weight effects when aircraft and nozzle types are combined with release height.

Wind Direction

Swath width and buffer distance are both strongly affected by changes in wind direction, as the smaller drop sizes drift downwind.

Wind Speed

Swath width increases with increasing wind speed, except for the smaller drop sizes, which may actually exhibit a decrease in swath width with increasing wind speed (as the released spray drifts further downwind). Buffer distance always increases with increasing wind speed.

Nonvolatile Fraction

Swath width exhibits very little effect due to increases in nonvolatile fraction.

Wet Bulb Temperature Depression

Swath width exhibits very little effect due to increases in wet bulb temperature depression (temperature and relative humidity), except for the smaller drop sizes. Buffer distance increases with increasing wet bulb temperature depression, especially for lower

release height. Temperature and relative humidity are seen to be important variables in downwind drift.

Nozzle Type

Swath width (and buffer distance) decrease strongly with increase in VMD (especially below 200 μm).

Specific Gravity

Swath width decreases with increasing specific gravity, but only for the smaller drop sizes.

Overall, this sensitivity study has quantified the effect on swath width for the variables considered. Not surprisingly, the trends shown for this study may, in some cases, be easily generalized (such as for release height, wind direction, wind speed, nonvolatile fraction, and nozzle type), but not so easily ascertained for others (boom width, spraying speed, aircraft weight, wet bulb temperature depression, and specific gravity).

7. Conclusions

This study provides an essential database for enhancement of FSCBG model development. With a broad set of input variable sensitivities, and detailed FSCBG model predictions (especially for many aircraft and nozzle types), we have generated a large database of ground deposition patterns for use in training and operation use, and sensitivity options within SpraySafe Manager and FSCBG. These results confirm most results from a previous sensitivity study, and disclose several new findings as follows:

1. We have confirmed results from the previous sensitivity study, namely the importance of the boom width, release height, spraying speed, wind direction, wind speed, nonvolatile fraction, temperature and relative humidity, volume median diameter (especially for drop sizes below 200 μm), and specific gravity. The importance of smaller drops cannot be overstated here, as they are generally most influenced by changes in input variables, and are directly related to downwind drift.

2. We have determined that several previous conclusions were in error, simply because we did not include a large enough sampling of aircraft and nozzle types in our first sensitivity study. These revised results include the importance of spraying speed (for smaller drops, swath width increases with spraying speed increase), aircraft weight (rotary atomizers are especially sensitive to changes in aircraft weight), wind speed (the influence of wind speed blowing smaller drop sizes off the computational grid), and nonvolatile fraction, temperature and relative humidity (smaller drop sizes are especially sensitive to changes in these three variables).

8. References

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